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Evaluation of the Flail Space Model Utilizing Event Data Recorder Technology

Douglas John Gabauer

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ABSTRACT

Developed in the early 1980's, the flail space model has become the standard method for estimating occupant risk in full-scale crash tests involving roadside safety features. The widespread availability of airbags and increased seat belt usage rates in today's vehicle fleet, however, raise serious questions regarding the validity of the model. Recent implementation of Event Data Recorder (EDR) technology in a number of late model vehicles presents a different perspective on the assessment of the validity of occupant risk based on the flail space model. EDRs are capable of electronically recording data such as vehicle speed, brake status and throttle position just prior to and during an accident. Of particular interest is the EDRs ability to document the deceleration of a vehicle during a collision event. This thesis presents a methodology utilizing EDR data to investigate the capability of the flail space model to predict injury to airbag-restrained occupants. Results of a preliminary analysis are presented based on implementation of the developed methodology on a limited data set.

A major part of the analysis is limited to the occupant impact velocity due to complications in estimating the occupant ridedown acceleration from the available EDR data. The longitudinal occupant impact velocity is found to be a good predictor of overall injury, chest injury and, to a lesser extent, lower extremity injury. For the head, and upper extremity body region, the longitudinal occupant impact velocity is a weak predictor of injury. In the analyzed data set, the occupant impact velocity is found to be more significant predictor of overall occupant injury than the occupant ridedown acceleration.

CHAPTER 1 – EVOLUTION OF OCCUPANT RISK CRITERIA

1.1 Vehicle Crashworthiness

Full-scale crash testing has been the traditional method of evaluating the crashworthiness of motor vehicles and can be traced back as far as the late 1950's [1]. The purpose of these tests is to gauge how well a particular vehicle protects the occupants in a given collision mode (e.g. frontal, frontal offset, side impact). Figure 1 shows an illustration of typical vehicle collision modes utilized in full-scale crash tests. Note that in typical tests, a surrogate is used for the other vehicle. For instance, a vehicle impacting a stationary barrier is used to simulate the full frontal crash mode. Federal Motor Vehicle Safety Standard (FMVSS) 208 [2] and FMVSS 214 [3] have been mandated to ensure a minimum crashworthiness of new vehicles in the frontal and side collision modes, respectively.

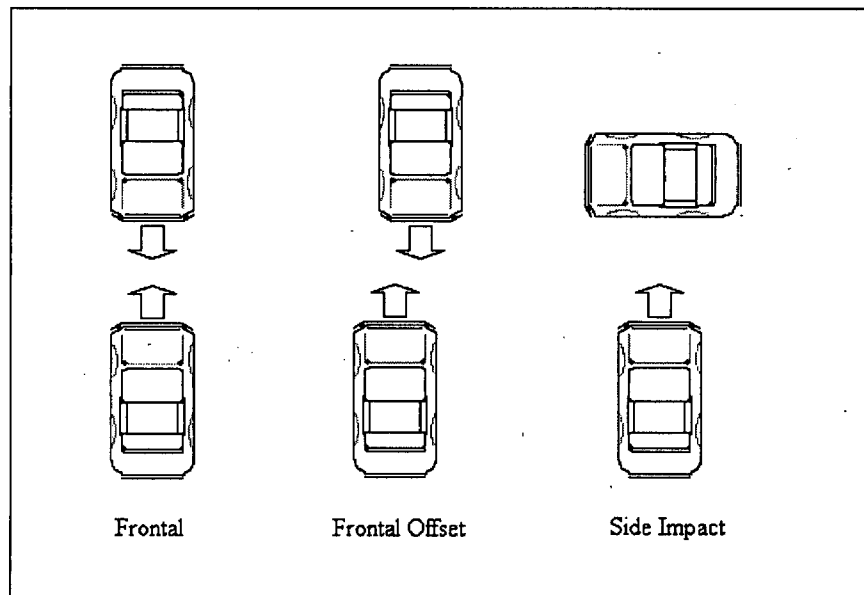


Figure 1. Examples of Vehicle Collision Modes

The National Highway and Traffic Safety Administration (NHTSA) maintains a database of full-scale crash tests to facilitate vehicle crashworthiness research. Included in this database is information pertaining to New Car Assessment Program (NCAP) tests. These tests are conducted to ensure that new vehicles comply with FMVSS 208 [2] and FMVSS 214 [3]. Figure 2 is a photograph of a 2003 Jaguar X-Type 4-door sedan after a NCAP frontal barrier test. In this case, the vehicle was propelled into a stationary barrier at thirty-five (35) miles per hour.



Figure 2. 35 MPH NHTSA Frontal Barrier Test

To provide a better understanding of these staged crash tests, detailed information is collected with respect to the kinematics of the vehicle. Accelerometers are placed at different locations on the vehicle to track the motion of these portions of the vehicle. High-speed photography is also used to document the dynamic deformation of the vehicle and provide an overall documentation of the impact. In the frontal barrier collision illustrated in Figure 2, load cells are situated in a grid on the barrier to measure the distribution of forces produced by the impacting vehicle. The uniform collection of this

detailed data is facilitated through the use of a standard published by the Society of Automotive Engineers (SAE), SAE-J211 [4]. This document includes specifications for the minimum sampling frequencies for accelerometers, the calibration and accuracy of these devices, as well as the filters to be used in the manipulation of the gathered electronic data.

One measure of the vehicle crashworthiness in these crash tests is how well the occupants of the vehicle are protected from injury during a collision. Obviously, moral and legal implications prevent the use of human subjects in full-scale crash tests, which are likely to produce injury. Instead, Anthropomorphic Test Devices (ATDs) have been developed to mimic the human response during a crash test. Figure 3 presents an image of a Hybrid III 50th percentile male ATD used in full-scale crash tests. Typically referred to simply as crash test dummies, these devices are precisely instrumented to track the forces, accelerations and deflections that the ATD experiences during an impact. These measured values are then used to provide an indication of the potential for occupant injury. Note that ATDs are manufactured in different sizes and shapes in an attempt to provide a representation of a larger portion of the human population. Examples include the 50th percentile male ATD, which is utilized in most of the frontal barrier crash tests, the 5th percentile female, and the 95th percentile male. The percentile values associated with the ATD models indicate the percentage of humans in the population below the height and weight of the particular ATD. For instance, five (5) percent of the females present in the population are smaller, in terms of height and weight, than the 5th percentile female ATD. Also note that ATDs are designed for particular collision modes, as different injury mechanisms are present for different impact orientations of the human

anatomy. Although several specialized ATDs exist, the majority of the ATDs are classified for use in either frontal or side impacts.

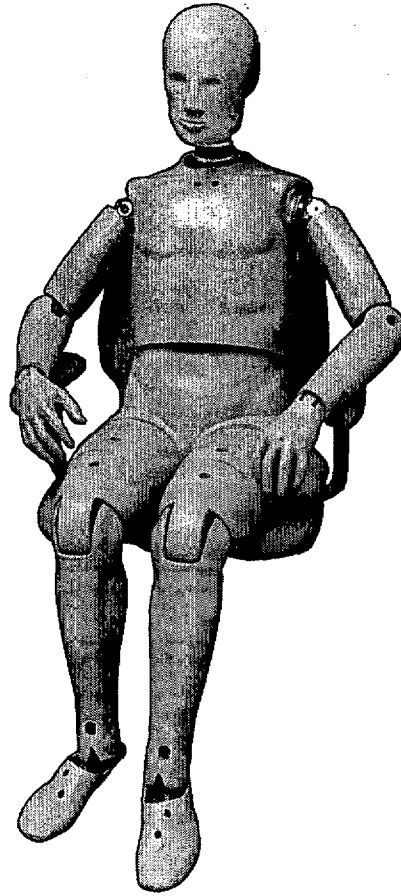


Figure 3. Typical ATD Utilized in Full-Scale Crash Tests

1.2 Roadside Safety Features

Roadside feature is a general term that encompasses any fixture on, near or above a roadway. Examples include overhead directional signs, light fixtures, curbs, temporary detour signs, and roadside ditches. Roadside safety hardware refers to the specific subset of roadside features installed to provide a forgiving roadside environment in the event a vehicle departs from the roadway. These devices can redirect a vehicle away from a more hazardous object, breakaway in the event that it is struck, or bring a vehicle to a controlled stop. The American Association of State Highway and Transportation

Officials (AASHTO) Roadside Design Guide [5] provides guidelines for the selection and placement of roadside safety hardware.



Figure 4. Three-Strand Cable Longitudinal Median Barrier: Interstate 78, Hunterdon County, NJ

Typically, these devices are classified into the following four categories: longitudinal barriers, crash cushions/end terminals, breakaway supports, and work zone devices. The purpose of longitudinal barriers is to shield vehicles from a more dangerous roadside hazard (e.g. tree, steep slope, or jagged rock face) [5]. The rationale is that an impact with the longitudinal barrier will be less severe than an impact with the object it shields. An example of a longitudinal barrier, the three-strand cable barrier, is shown in Figure 4.



Figure 5. Crash Cushion Shielding an Overpass Support Pier: Route 280, Morris County, NJ

Similar to longitudinal barriers, crash cushions shield hazardous roadside objects and, in the event an errant vehicle strikes on an angle, will redirect the vehicle away from the hazard. For head-on impacts, however, these appurtenances are designed to gradually decelerate a vehicle to a stop in a controlled manner [5]. Figure 5 shows a crash cushion shielding an overpass support pier. Several guardrail end terminals, like the one illustrated in Figure 6, can be classified as crash cushions designed to ensure a safe termination of a longitudinal barrier.



Figure 6. ET-2000 Guardrail End Terminal: Route 658, Gloucester County, NJ

Breakaway supports are designed to yield in a predictable manner when impacted by a vehicle [5]. The “breakaway” mechanism is used to support roadside features that must be placed near the roadway (e.g. roadway signs, roadway lights, or traffic signals). To allow for predictable fracture, these devices typically utilize a slip plane, fracture element, or plastic hinge. Figure 7 shows a breakaway base of a traffic light support. Work zone devices are the subset of roadside safety features developed specifically for use in roadway construction areas. Safety features included in this category are temporary longitudinal barriers, temporary crash cushions, truck mounted attenuators, traffic cones, drums, and work zone signs and supports. A temporary concrete barrier, used to protect construction workers and construction vehicles from nearby traffic, is shown in Figure 8.

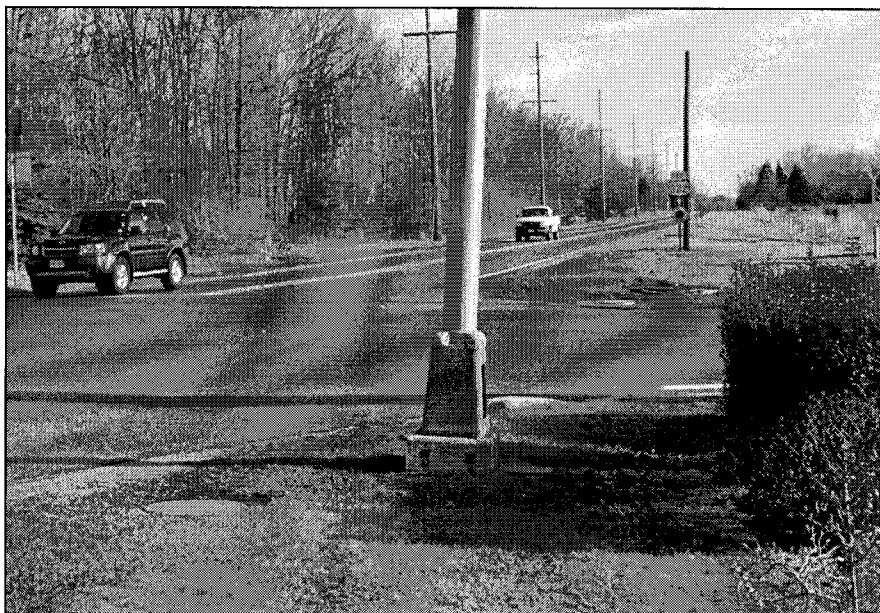


Figure 7. Frangible Base Traffic Signal Support: Intersection of Route 322 and Route 655, Gloucester County, NJ



Figure 8. Temporary Concrete Median Barrier: Southbound Interstate 295, Burlington County, NJ

1.3 Performance Evaluation of Roadside Safety Features

Similar to vehicle crashworthiness appraisal, full-scale vehicle crash testing is utilized to ensure the effectiveness of roadside safety hardware. Formalized roadside

hardware testing procedures have been evolving since the publication of the first guidelines in 1962 [6]. Periodic updates to these procedures occur primarily because of improvements in the understanding of the mechanics of roadside safety hardware collisions and/or significant changes to the vehicle fleet. The published roadside hardware testing procedure guidelines are as follows:

- Highway Research Board Circular 482 [6]
- NCHRP Report 153 [7]
- Transportation Research Circular 191 [8]
- NCHRP Report 230 [9]
- NCHRP Report 350 [10]

Figure 9 presents a chronological schematic of the publication of these documents. To provide a general notion of the development of these procedures, the Highway Research Board Circular 482 [6] consisted of a single page, while the current guidelines, NCHRP Report 350 [10], consists of over one hundred (100) pages.

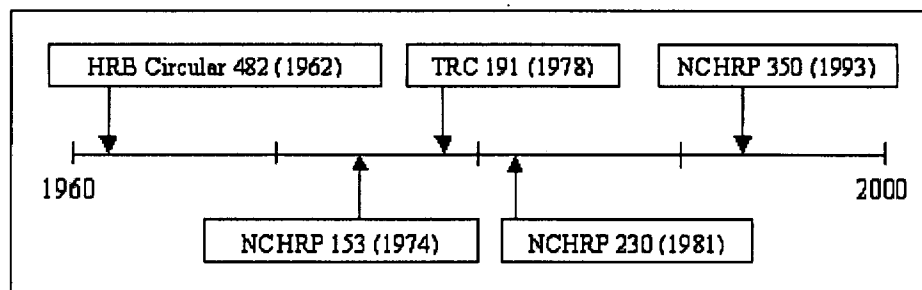


Figure 9. Roadside Hardware Test Procedure Publication Timeline

The intent of the current guidelines [10] is to provide a framework for the uniform testing and evaluation of the safety performance of roadside features and hardware. To facilitate this objective, the guidelines provide specifications for the test configuration (e.g. device installation), impact conditions (e.g. vehicle speed, approach angle, and

impact point on the device), standardized test vehicles, data collection procedures, and evaluation procedures. As countless installation configurations of these devices are possible, the guidelines recognize that crash testing of each configuration is not viable. Instead, the deliberate approach is to test at specific “normalized” conditions. For instance, all guardrails are to be installed straight on a flat slope although some roadways have these devices installed in a curved configuration, or on a slope, or both. Similarly, for practical testing purposes, the infinite vehicle impact conditions possible are narrowed to represent the practical worst-case scenario for each device. The assumption is that if the device can perform satisfactorily under these severe conditions, then the performance will be appropriate for the spectrum of impacts including all less rigorous impacts. An analogous situation exists for the selection of test vehicles, as testing each device with each production vehicle model is impractical. To provide a reasonable number of standard test vehicles while incorporating the performance characteristics of the entire fleet, selection is such that each extreme of the vehicle fleet is represented. This “standardized” approach to testing of roadside features allows for a valid comparison between roadside safety hardware devices.

Recognizing a need for varying performance requirements for the diverse roadway types, the guidelines specify up to six test levels (1 through 6), which differ primarily by impact conditions. Although these test levels are provided, the document does not specify warrants for the various test levels (i.e. devices meeting a particular test level are not specified appropriate for a given roadway or purpose). This decision is left to the discretion of the user agency (e.g. a State Department of Transportation). In general, however, the lower test levels are typically for lower traffic and lower speed

applications while the higher test levels are for higher traffic and higher speed applications [10]. Note that test level three (3) corresponds to the level typically used for most roadside hardware applications.

Data collection procedures are similar to those used in full-scale vehicle testing procedures and significant reference is made to SAE-J211 [4]. Important vehicle parameters obtained include the impact/exit speed, impact/exit angle, and vehicle acceleration with respect to time. With respect to the roadside hardware device, the data collected includes dynamic deformation of the device and the location of the impact point. Most of the data collected is obtained through the use of high-speed cameras, accelerometers, and rate gyros.

Once the data is collected from the completed crash test, the evaluation of a device is a three-tiered approach as specified by NCHRP Report 350 [10] and outlined below:

- Structural Adequacy
- Post-Impact Vehicle Trajectory
- Occupant Risk

Structural adequacy refers to how well the device performs its intended task (i.e. a guardrail preventing a vehicle from striking a shielded object) while the post-impact vehicle trajectory ensures that the device will not cause subsequent harm (i.e. a vehicle being redirected into opposing traffic). Similar to the purpose of the ATD in a vehicle crashworthiness test, the occupant risk criteria attempts to quantify the potential for severe occupant injury.

As the purpose of roadside safety hardware is to be functional while minimizing risk of injury to the occupants, the occupant risk criteria is vital to the assessment of these devices. The ATDs developed for use in determining occupant risk in full-scale vehicle crashworthiness testing have been developed specifically for the purpose of simulating the human response in frontal and side impact collisions. Roadside hardware collisions, however, have a greater propensity for oblique impact angles. To date, no ATD has been developed which can accurately reproduce the human response in this crash mode. Instead, the flail space model has been developed and implemented to evaluate occupant risk in roadside safety hardware crash tests.

1.3.1 Initial Occupant Risk Evaluation Criteria

Before the advent of the flail space model, the evaluation of occupant risk focused on establishing limitations on vehicular decelerations. These criteria appeared in NCHRP Report 153 [7] guidelines and in the subsequent TRC 191 [8] guidelines under the guise of “impact severity”, although the ultimate intent was to gain an estimate of occupant risk. The underlying assumption is that there is a relationship between the vehicle dynamics and the potential for occupant injury; presumably, the lower the maximum vehicle decelerations and change in momentum, the lower the potential for severe occupant injury. The authors of these guidelines, however, caution that this relationship is “tenuous” and affected by numerous other factors including occupant differences and vehicle interior padding differences. Although the “impact severity” evaluation guidelines are specified in excruciating detail in the guidelines, the authors warn that these evaluation procedures “...are not directly applicable to the complex highway collision” [8].

For collisions with longitudinal barriers ($<15^\circ$ impact angle), NCHRP Report 153 [7] specifies limits on the longitudinal, lateral and total 50 millisecond (50-ms) average accelerations of the vehicle during the impact (as measured at the center of mass of the vehicle). The NCHRP Report 153 acceptable limits for each direction are shown in Table 1. For the determination of the “total” category, the guidelines do not provide a clear explanation as to whether this is found by simply by adding the lateral and longitudinal accelerations or by evaluating the resultant accelerations. ATDs are prescribed as optional in these tests and the response must be consistent with the FMVSS 208 [2] frontal impact regulations. For crash cushion impacts and guardrail end terminals where the vehicle is decelerated to a stop, the authors recommend a maximum average deceleration of 12 G, with the desirable average acceleration between 6 G and 8 G. For breakaway or yielding sign supports, a maximum momentum change of 1100 lb-s is prescribed.

Table 1. NCHRP Report 153 Redirection Impact Severity Thresholds [7]

Peak 50-ms Vehicle Accelerations (G)			
Category	Longitudinal	Lateral	Total
Preferred	5	3	6
Acceptable	10	5	12

As the purpose of TRC 191 [8] was to address minor issues with NCHRP Report 153 [7] in the interim period prior to the publication of improved procedures (i.e. NCHRP Report 230 [9]), a majority of the prescribed occupant risk criteria was retained. The redirection criteria based on the 50-ms maximum vehicle acceleration and the limiting values shown in Table 1 remained unchanged. Minor changes, however, were made in the optional anthropomorphic test dummy response criteria and additional details were provided for occupant crash tolerance in breakaway/yielding support tests.

1.3.2 Development of the Flail Space Model

Problems with the “impact severity” method of evaluating occupant risk were expressed both by Chi [11] and Michie [12]. The most obvious relates to the piecewise approach utilizing peak 50-ms acceleration, average deceleration, and momentum change for longitudinal barrier, crash cushion, and breakaway device collisions, respectively. Using different methods to evaluate various roadside hardware devices caused confusion among researchers, highway agencies and hardware developers. In addition, the criterion may have been overly conservative in some areas. With respect to the longitudinal barriers, the concrete median barrier, although widely implemented, typically did not satisfy the preferred peak 50-ms acceleration values set by NCHRP Report 153 [7]. In addition, for crash cushions that do not decelerate the vehicle in a smooth manner, the occupant may be subjected to accelerations in excess of the average acceleration value (over the entire event). In an attempt to unify the previous occupant risk criteria, Michie [12] formally introduced the flail space model in 1981. In contrast to the previous piecewise approach, the flail space model provides a single, unified measure of occupant risk regardless of the appurtenance being evaluated and is more indicative of the physical phenomena involved. The model was developed in conjunction with NCHRP Report 230 [9], the update to the NCHRP Report 153 [7] procedures.

The flail space model simplifies the occupant-vehicle interaction during a collision into an event with two distinct phases [12]:

- (1) After vehicle impact, the occupant remains at the pre-impact vehicle velocity while the vehicle compartment surfaces accelerate toward the occupant. The

occupant impacts an interior surface of the vehicle (e.g. the dash, windshield, or steering wheel).

- (2) After occupant contact with the interior of the vehicle, the occupant remains in contact with the interior surface and is subjected to the same acceleration forces as the vehicle.

According to the hypothesis, there are two possible injury mechanisms. First, injury can occur at the conclusion of the first phase if the difference in velocity between the occupant and the occupant compartment, termed the occupant impact velocity, is excessive. Secondly, the occupant can sustain injury during the second phase, or occupant ridedown phase, if the magnitude of the vehicle accelerations subsequent to the occupant-interior impact is excessive.

To utilize the flail space hypothesis to determine occupant injury potential in full-scale crash tests, several simplifying assumptions are necessary (summarized from Michie [12]). First, the occupant is assumed to be an unrestrained lump mass positioned at the center of mass of the vehicle. Distances that the occupant is allowed to “flail” prior to impacting the vehicle interior are based on a 50th percentile male in a normal upright and seated position inside a vehicle. The values chosen to represent a typical vehicle interior are 0.6 meters (2 feet) in the longitudinal direction (parallel with the typical vehicle direction of travel) and 0.3 meters (1 foot) in the lateral direction. These values assume that the occupant compartment remains intact with no inward penetrations or collapses. A pictorial representation of the geometric simplifications of the flail space model is presented in Figure 10.

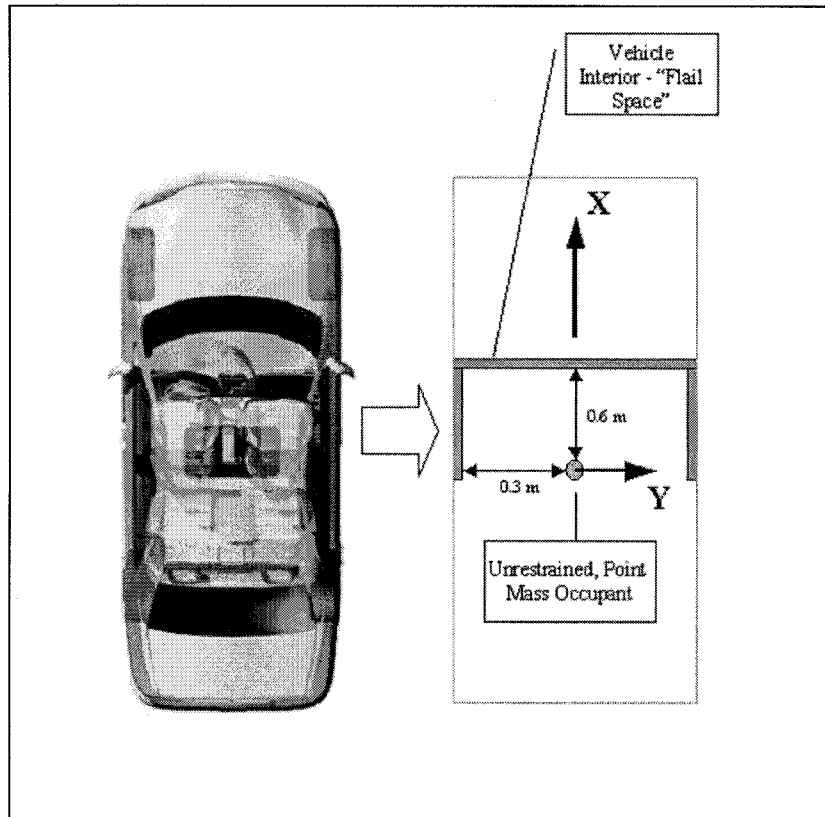


Figure 10. Flail Space Model Simplifications

Simplifications also have to be made with respect to occupant and vehicle motion. In the event of collision, the unrestrained point mass is assumed to behave as a “free missile”. Since vehicle accelerations are typically measured near the vehicle center of mass, these assumptions allow the occupant position and velocity functions to be calculated directly from the measured vehicular accelerations. Although an actual unrestrained occupant during a collision may experience several collisions with the vehicle interior, the model assumes that the initial occupant collision with the interior of the vehicle is completely inelastic. Thus, the occupant remains in contact with the contacted surface for the remainder of the collision event and any accelerations of the vehicle are transferred to the occupant through this contact. To further simplify the calculations involved, the vertical accelerations are assumed negligible, the lateral and

longitudinal motions of the occupant are assumed independent, and the roll, pitch and yaw motions of the vehicle are ignored (see Figure 11). As the testing procedures require that the vehicle remain upright and (for longitudinal barriers) is smoothly redirected, the vertical accelerations are of sub-critical importance in comparison to the horizontal motions. Since the front seat occupants are near or just behind the center of mass of the vehicle, any moderate vehicle roll, pitch and yaw should have only a minor effect on occupant kinematics.

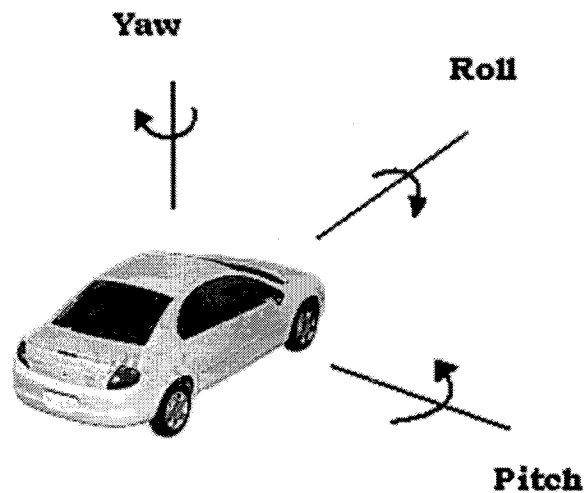


Figure 11. Graphical Representation of Vehicle Roll, Pitch, and Yaw

The flail space concept, as formally introduced by Michie [12], is summarized in NCHRP Report 230 [9] and appended with more detailed calculation procedures. Note that in addition to the flail space model, the occupant risk criteria presented also requires that the vehicle remain upright during the event and that the occupant compartment

remains intact (both are intrinsic assumptions of the flail space model). The calculation procedure for the occupant impact velocity is as follows [9]:

1. Filter vehicular acceleration (measured from vehicle center of mass during impact) information with SAE-J211 [4] Class 180 filter.
2. Determine the value of t_x^* and t_y^* for longitudinal and lateral directions, respectively:

$$0.6meters = \int_0^{t_x^*} \int_0^{t_x^*} a_x dt^2$$

$$0.3meters = \int_0^{t_y^*} \int_0^{t_y^*} a_y dt^2$$

The time to occupant impacting the interior, t^* , is the smaller of t_x^* and t_y^* .

3. Determine the longitudinal (X) and lateral (Y) component of the occupant impact velocity using the following:

$$V_{I_{X,Y}} = \int_0^{t^*} a_{X,Y} dt$$

4. For tests where the vehicle impact conditions vary from the target impact conditions, the following is used to normalize the occupant impact velocity to the target conditions:

$$(\Delta V)^* = (\Delta V) \cdot \frac{(V \sin \theta)_{TARGET}}{(V \sin \theta)_{ACTUAL}}$$

where $(\Delta V)^*$ is the normalized occupant impact velocity, (ΔV) is the occupant impact velocity for the test conditions, $(V \sin \theta)_{TARGET}$ is the intended impact conditions (V is the vehicle velocity and θ is the impact angle), and $(V \sin \theta)_{ACTUAL}$ is the actual impact conditions. Note that this correction is

more critical for redirection barrier collisions and side impacts into crash cushions.

The calculation procedure for the occupant ridedown acceleration is as follows [9]:

1. From the calculation of the occupant impact velocity, identify the value of t^* .
2. After $t = t^*$, compute a 10 ms moving average of the filtered vehicle acceleration values in both the longitudinal (X) and lateral (Y) directions. The largest 10 ms average value in either direction is the occupant ridedown acceleration (two values are produced).

Once the occupant impact velocity and occupant ridedown acceleration values are computed, the values are compared to threshold values to ensure that the risk of occupant injury is not excessive. Note that all values must be below the threshold limits in order for the device to be acceptable with regard to occupant risk. Table 2 shows the original occupant risk threshold values as suggested by Michie [12] and NCHRP Report 230 [9]. Note that the “limit” values refer to upper threshold values derived from biomechanics research. These upper values are then divided by a safety factor, F , to determine the “design” or desirable occupant risk values. Although values below the “design” values are preferred, values below the “limit” values are considered acceptable.

Table 2. NCHRP 230 Occupant Risk Thresholds [9]

Impact Direction -Hardware Type	Occupant Impact Velocity			Occupant Ridedown Acceleration		
	ΔV_{Limit} (fps)	F (Safety Factor)	ΔV_{Design} (fps)	A_{Limit} (g)	F (Safety Factor)	A_{Design} (g)
Longitudinal (X)						
Breakaway signs and luminaries	40	2.67	15	20	1.33	15
All others	40	1.33	30	20	1.33	15
Lateral (Y)						
Redirectional Barriers	30	1.50	20	20	1.33	15

Consistent with the procedures used to evaluate the ATD responses in vehicle crashworthiness testing, an attempt has been made to set the threshold levels such that the upper design limits will produce severe but not life-threatening injury [12]. The human injury tolerance and accident research utilized to facilitate this objective are summarized in Michie [12] and NCHRP Report 230 [9]. The occupant impact velocity limit in the longitudinal direction was based principally on head impact experiments into windshields [13,14]. The lateral threshold was based mainly on a French accident statistics [15] and research aimed at developing FMVSS 214 [3], the U.S. vehicle standard for side impact protection. Occupant ridedown acceleration threshold values have been established mainly from exhaustive human impact tolerance review documents from the 1970's [11,16].

1.3.3 Permutations of the Flail Space Model

Compared to the previous occupant risk procedures, the flail space model provides a more physically correct determination of occupant injury potential. Despite this fact, researchers have long attempted to improve the model, typically through modifications to the simplifications of the original model. Most notable variations of the flail space model are as follows:

- Ray et al. [17]
- Ross et al. [18]
- Ray and Carney [19]
- European Committee for Normalization (CEN) [20, 21]

All the variations incorporate vehicle yaw motion and utilize the coupled equations of motion (lateral and longitudinal motions are not assumed independent). The Ray et al.

[17] algorithm also tracks the position of the occupant with respect to its original position and the relative velocity with respect to the vehicle interior at each time interval. Additional features of the Ross et al. [18] version is a more exact “flail” space that accounts for different occupant seating locations (i.e. the driver can “flail” in excess of one foot laterally to the right) and a more exact tracking of the occupant movement. For instance, if the occupant impacts the side of the vehicle first, the lateral component of the velocity is set to zero but the algorithm continues to track the occupant’s longitudinal motion. The Ray and Carney [19] version also tracks the occupant position beyond the initial impact but accounts for rebound. At each impact with the vehicle interior, the algorithm determines the velocity normal to the contacted boundary and subtracts it from the occupant velocity in that direction to determine the rebound velocity.

The European Committee for Normalization (CEN) [20,21] has adopted a modified method of occupant risk evaluation in vehicle-to-roadside hardware tests that involves the computation of the Theoretical Head Impact Velocity (THIV), the Post-Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI). With respect to the flail space model, the THIV is equivalent to the occupant impact velocity while the PHD is equivalent to the occupant ridedown acceleration. Both differ slightly computationally, however, with the CEN version utilizing the coupled equations of motion and the resultant velocity and acceleration values (rather than separating lateral and longitudinal components). In addition, the ASI is employed to account for occupants utilizing passive restraints (i.e. the occupant motion is closer to that of the vehicle motions) and is found using the following relation:

$$ASI(t) = \left[\left(\frac{\bar{a}_x}{\hat{a}_x} \right)^2 + \left(\frac{\bar{a}_y}{\hat{a}_y} \right)^2 + \left(\frac{\bar{a}_z}{\hat{a}_z} \right)^2 \right]^{\frac{1}{2}}$$

where \bar{a}_x , \bar{a}_y , and \bar{a}_z are the 50-ms average component vehicle accelerations and \hat{a}_x , \hat{a}_y , and \hat{a}_z are corresponding threshold accelerations for each component direction. The maximum ASI value over the vehicle acceleration pulse duration provides a single measure of collision severity.

1.3.4 Current Flail Space Model

Despite the numerous model variations, the NCHRP Report 350 [10] flail space model is virtually identical to the procedure presented by Michie [9,12]. Only minor changes have been made, including a conversion to metric units and a computation clarification. For the case where the occupant does not reach either flail space threshold (0.6 meters longitudinally or 0.3 meters laterally), NCHRP Report 350 [10] specifies that the occupant impact velocity be set equal to the vehicle velocity change occurring during vehicle contact with the test article. If the device remains in contact with the vehicle after impact, the velocity change is computed from the time when the vehicle clears the footing of the test article. Note that this is generally applicable to shorter duration tests (e.g. impacts with breakaway poles or supports).

Similarly, the NCHRP Report 350 [10] threshold values reflect only minor changes to the NCHRP Report 230 [9] threshold values. Table 3 presents the current NCHRP Report 350 [10] threshold occupant risk values. Retention of the original threshold values was based on consultation with biomechanics experts, a General Motors (GM) research study [22], an evaluation report of NCHRP Report 230 guidelines [23],

and an investigation of impact attenuator systems [24]. Note that rounding during the conversion to the SI system produced slightly different values and that the lateral occupant impact velocity threshold value was increased to match the longitudinal occupant impact velocity threshold. The increase in the lateral occupant impact velocity threshold was prompted by the conclusion of Ray et al. [23] that the lateral occupant impact velocity was overly conservative for redirection collisions. In addition, since NCHRP Report 230 provided no occupant impact velocity limits for support structures and work zone devices, thresholds of 3 m/s preferred and 5 m/s maximum are prescribed by NCHRP Report 350 [10] (not shown in Table 3). The selected values are consistent with those previously adopted by AASHTO [25] for breakaway devices.

Table 3. Current Occupant Risk Threshold Values [10]

Occupant Impact Velocity Limits		
Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	9 m/s	12 m/s

Occupant Ridedown Acceleration Limits		
Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	15 g	20 g

Although the flail space model remained relatively unchanged, the following modifications were considered in the development of the NCHRP Report 350 [10] guidelines:

- Positioning of the occupant in the driver and/or right front seat occupant position.
- Accounting for the yaw motion of the vehicle.

- Altering the dimensions of the occupant compartment to reflect the actual flail distances (i.e. the driver can “flail” in excess of 0.3 meters laterally to the right).

The following arguments have been provided for not incorporating these modifications (summarized from [10]). Although altering non-critical factors, inclusion of vehicle yaw motion and variable occupant positioning would not have a significant effect on the occupant risk measured in typical barrier collisions. Altering the dimensions of the occupant compartment to allow a more realistic lateral flail space would disqualify a majority of redirectional devices based on the current occupant risk threshold values. Since there is no strong evidence that the current devices are performing inadequately in service and that the flail space model is used merely as an indicator of occupant injury potential, the authors argue that the occupant compartment changes are not warranted.

At the time of publication, an update to the NCHRP Report 350 procedures was being prepared under NCHRP Project 22-14(2). The assessment of the need for an update to the performance testing guidelines was completed under NCHRP Project 22-14(1) and summarized in the corresponding final report [26]. With respect to the occupant risk criteria, consideration was given to the use of instrumented ATD's, computer simulation models, and the adoption of the CEN version of the flail space model. Primarily due to the cost involved and the lack of validation in the oblique crash mode, the use of ATD's in roadside hardware crash tests was argued infeasible. Computer simulation was indicated as a viable option; however, additional validation is required for the oblique crash mode. Excluding the ASI criterion, the study recommends the adoption of the CEN version of the flail space model.

1.4 *The Flail Space Model and Actual Occupant Injury*

Although the intent of the flail space model is to indicate occupant injury potential, there has been little research to date characterizing the model's relationship to actual occupant injury. The ideal method of establishing a relationship would involve the use of human subjects in full-scale crash tests; however, this is not employed due to the obvious moral and legal implications. Previous research has utilized real-world accident data since the occupant injury information is available. Because the real-world accident data lacks detailed data pertaining to the vehicle kinematics, however, the link between the flail space model and occupant injury remains tenuous at best.

Stewart and Council [27] utilized accident data in an attempt to link occupant risk (as calculated in crash tests) to actual injury attained in collisions. The procedure matched instrumented full-scale crash tests with similar vehicle characteristics (make, model and year), crash characteristics (object struck, impact location on vehicle, etc.), and crash severity (as measured by vehicle deformation) in actual crashes. Results of this study indicated the lack of a strong relationship between injury severity and vehicle momentum change and 50-ms peak acceleration values. With regard to the flail space model, the limited amount of data in the study prevented any conclusions. An approximate comparison done by Michie [12], though, suggests that there is not a significant disparity between the previous 50-ms criterion and the occupant impact portion of the flail space model.

In another study, Ray et al. [28] investigated the occupant injury mechanisms in longitudinal barrier collisions. The effort was particularly focused on the lateral occupant impact velocity since a series of side impact sled tests, performed as part of the study,

indicated that the current threshold might be overly conservative. By reconstructing seventeen (17) longitudinal barrier accidents that produced severe occupant injury, the authors found that the lateral component of the first impact was not the cause of the serious injury in any case. The authors concluded that, although it is a useful tool for the estimation of occupant risk, the flail space model does not appear to be a discerning factor in redirection crash tests.

1.5 *The Flail Space Model Revisited*

The intent of the flail space model is to provide a gross indication of the likelihood of severe occupant injury to facilitate proper evaluation of roadside hardware devices. For highway collisions, however, occupant injury involves complex and widely varying interactions between the occupant, the vehicle, and the vehicle safety systems. Occupant injury is affected by a myriad of factors including, but not limited to, occupant physical condition, restraint usage, and seating position, as well as vehicle crashworthiness, interior geometry, and interior padding. Although the authors of NCHRP Report 350 argue that the redirection features designed according to the flail space model “appear to be performing satisfactorily” [10], perhaps the current model is not the optimum method of estimating occupant injury potential. Potential problematic aspects of the current model include the basis for threshold values, the validity of the assumptions, especially with respect to the current vehicle fleet, and the general lack of understanding of the correlation to actual occupant injury.

Although developed using the current state-of-the-art in human injury tolerance research, the threshold values are based only on a limited number of experimental data. The longitudinal occupant impact velocity thresholds are based primarily on 38 [13], 99

[14], and 3 [23] frontal sled test sets performed at impact speeds up to 55 km/hr (15 m/s), 60 km/hr (17 m/s) and 50 km/hr (13.7 m/s), respectively. All three studies utilized an ATD to infer potential occupant injury potential via the Head Injury Criterion (HIC), a method developed by NHTSA to assess head injury risk for occupants involved in frontal collisions. Human injury tolerance data is even more limited in the lateral direction; the original lateral occupant impact velocity threshold of 20 fps (6 m/s) was based principally on a total of 296 lateral impacts obtained from 6 years of French accident data starting in 1970 [15]. For the current NCHRP Report 350 procedures, the increase of this value to 30 fps (9 m/s) was prompted by a total of 17 reconstructed longitudinal barrier collisions [23]. Due to the extensive amount of research done in the aeronautics field on tolerable limits of acceleration, the occupant ridedown acceleration limits are based on a more extensive research base. The current lateral and longitudinal limiting value of 20 g was chosen based on an extensive literature review by Snyder [16] and a critical review (Chi [11]) of the occupant risk procedures used prior to the flail space model. Snyder indicates, however, that only few of human tolerable limits to impact stress "...have been even grossly defined." [16].

With respect to the simplifying assumptions of the flail space model, the numerous variations [17,18,19,21] of the model indicate the general interest in improving the original model. Analyses have been performed to determine the potential error associated with some of the simplifying assumptions. For the exclusion of the yaw rate of the vehicle, Ray et al. [17] found an error less than 6 percent for redirection tests. Ray and Carney [19] investigated the effect of acceleration transducer placement and the inclusion of the coupled equations of motion on the calculated occupant risk parameters.

For a transducer located within 12 inches of the vehicle center of mass, the measured accelerations are determined to have an error up to 10 percent. Using two redirectional tests to investigate the independent motion assumption, an error of 5 percent was found but the authors hypothesized that this error would be much greater in the case of side or non-tracking (skidding) impacts. The implications of these potential error sources, however, have not been investigated with respect to the ability of the flail space model to indicate occupant injury risk.

The validity of the assumptions of the flail space model are also complicated by the evolution of vehicle technology and vehicle operating trends. At the inception of the flail space model in 1981, belt usage rates were less than 20% [12] and use of airbags was not widespread. Today, however, belt usage rates exceed 70% [29] and all passenger cars since model year 1997 are required to be equipped with driver and passenger airbags. Michie [12] indicated that the originally proposed thresholds might become conservative as the vehicle fleet becomes equipped with advanced restraints. Considering these facts, is the unrestrained occupant assumption overly conservative? There may also be significant differences in interior space dimensions in newer vehicles. Ray et al. [28] conducted a survey of vehicle interior dimensions (model years 1978 to 1984) and found the recommended flail space dimensions suitable. Are the dimensions prescribed still appropriate for the current vehicle fleet?

Another impediment is the tenuous understanding of the link between flail space model and actual occupant injury. As mentioned previously, only two studies [27,28] have attempted to characterize this linkage. There are inadequacies common to both available studies. As both studies were performed before the widespread implementation

of airbag technology, neither can address the implications of these advanced restraints. An understanding of the effect of advanced restraints on the flail space model is crucial to determining whether the model is still applicable to the current vehicle fleet. Both studies utilize the detailed vehicle kinematics information existing for full-scale crash tests, however, each lack this detailed information for the vehicles involved in the studied real-world collisions. This information is essential for the computation of the flail space criteria and the development of a correlation to occupant injury. Another complication, noted by Thomson [30], is the lack of investigation of oblique impacts. This would provide clarification as to whether it is valid to predict oblique human injury by using the lateral and longitudinal components of the applied oblique forces. In addition, neither study explores the relation between any of the flail space model variations and actual occupant injury.

A better understanding of the relationship between the flail space model and occupant injury is needed – particularly in light of the evolution of the vehicle fleet since the inception of the model. Perhaps the largest obstacle preventing researchers from linking the flail space model to occupant injury has been the lack of vehicle kinematics information for real-world collisions. As will be discussed in more detail, Event Data Recorder (EDR) technology may provide sufficient vehicle kinematics information to facilitate an evaluation of the flail space model for airbag-restrained occupants.

CHAPTER 2 – EDRS AND THE ROWAN UNIVERSITY DATABASE

2.1 *Event Data Recorder Technology*

Recent advances in vehicle technology have allowed for an unprecedented opportunity to obtain information during a highway traffic collision. One such technology is Event Data Recorders (EDRs), which are being installed in numerous late model vehicles in conjunction with the advanced occupant safety systems. These devices are similar to airplane “black boxes” as they record information in the event of a highway collision. Information typically stored by these manufacturer-specific devices includes seat belt status, deployment of the airbag, and vehicle speed prior to impact [31]. Of particular interest to this study is the EDR’s ability to record the deceleration of a vehicle during a collision event, data that can be used to compute the flail space criteria in real-world collisions.

2.1.1 Background

Initial efforts at implementing EDR technology can be traced as far back as the early 1970’s when NHTSA installed analog recording devices in approximately 1000 fleet vehicles [32]. Since then, significant technological advancements have been made in vehicle technology and, similarly, EDR technology. Current EDRs are typically split into two categories: original equipment manufacturer (OEM) devices and aftermarket devices. OEM devices are integrated with the vehicle airbag control module, the device that controls the deployment of advanced restraints. In the event of a collision, the OEM EDR records the information that triggers the deployment (or near deployment in some

instances) of the airbag. Although there is evidence that many vehicle manufacturers are equipping vehicles with EDRs, only two manufacturers, General Motors (GM) and Ford, have publicly released information pertaining to the presence and capabilities of these devices in their respective vehicles [33]. Unlike OEM EDRs, aftermarket systems are independent of the vehicle airbag control module. Also, since they are designed for particular purposes, the aftermarket systems typically differ by recorded parameters.

As GM and Ford are the only vehicle manufacturers that have publicly released EDR information, a more detailed description is provided for these OEM devices. Both the NHTSA EDR Working Group Final Report [31] and NCHRP Project 17-24 Final Report [34] provide more detailed information regarding EDR technology.

2.1.2 The GM EDR

Since 1994, GM has been equipping production vehicles with Sensing and Diagnostic Modules (SDMs), the GM version of the EDR [35]. Although several different types exist, a majority of vehicles are equipped with one of two units; the SDM-R is found on vehicles up to model year (MY) 1999 while the SDM-G is found on vehicles from MY 2000 [33]. The current GM SDM has the ability to record three types of events: non-deployment, deployment, and deployment level [34]. A non-deployment event occurs when there is a sufficient vehicle deceleration to trigger the “algorithm enable” but not to deploy the airbag. For a deployment event to occur, the vehicle has a deceleration sufficient to deploy the airbag. A deployment level event is a subsequent impact of sufficient severity to cause airbag deployment, however, the airbag had deployed in a previous event. Although the GM SDM can record three types of events, it only stores information pertaining to a total of two events [34]. For both recorded events,

however, the GM SDM can store information for the crash as well as up to 5 seconds preceding the crash [36]. The stored information is accessed via the Crash Data Retrieval (CDR) system, available only from the Vetronix Corporation [36]. Table 4 summarizes the data recorded by the GM SDM.

Table 4. GM EDR Recorded Data Elements [34]

Parameter Type	Parameter	Data Type	Values
1. General	Prior Deployment?	Coded	Yes/No
	Airbag Warning Lamp Status	Coded	On/Off
	Ignition Cycles @ Deployment	Integer	
	Ignition Cycles @ Investigation	Integer	
	Brake Switch State @ Algorithm Enable	Coded	Applied/Not Applied
	Brake Switch Validity Status	Coded	Valid/Invalid
2. Restraints	Driver Seat Belt Status	Coded	Buckled/Unbuckled
	Passenger Airbag Suppressed	Coded	Yes/No
	Driver Algorithm Enable to 1 st Stage Deployment [msec]	Floating Point	
	Driver Algorithm Enable to 2 nd Stage Deployment [msec]	Floating Point	
	Passenger Algorithm Enable to 1 st Stage Deployment [msec]	Floating Point	
	Passenger Algorithm Enable to 2 nd Stage Deployment [msec]	Floating Point	
3. Event Counters	Time [sec] between Non and Deployment	Floating Point	
	Frontal Deployment Level Event Counter	Integer	
	Event Recording Complete	Coded	Yes/No
	Multiple Events	Coded	Yes/No
	≥ 1 Events Not Recorded	Coded	Yes/No
	Time [sec] Between N and DL	Floating Point	
4. Pre-Crash Data	Vehicle Speed Vs. Time	Integer Array	
	Engine Throttle [%] Vs. Time	Integer Array	
	Engine Speed [rpm] Vs. Time	Integer Array	
	Brake Status Vs. Time	Coded Array	On/Off
5. Crash Pulse	Longitudinal Change in Velocity Vs. Time [mph]	Floating Point Array	
	Maximum EDR Velocity Change [mph]	Floating Point	
	Algorithm Enable to Max Velocity Change [ms]	Floating Point	

As the computation of the flail space model requires vehicle kinematics information, the longitudinal velocity change vs. time recorded by the GM EDR is of particular importance to this study. To determine the vehicle longitudinal velocity, the module integrates the average of four 0.312 millisecond vehicle acceleration samples [36]. Although the acceleration is sampled approximately three times per millisecond, the GM EDR only records velocity information every 10 milliseconds [36]. The duration of recording also varies based on the GM SDM; the older GM SDMs record vehicle velocity for up to 300 milliseconds while the newer versions only record for up to 150 milliseconds [34]. Figure 12 is a plot of the GM SDM longitudinal velocity change versus time for a 1999 Chevrolet Cavalier involved in a frontal collision with a pickup truck.

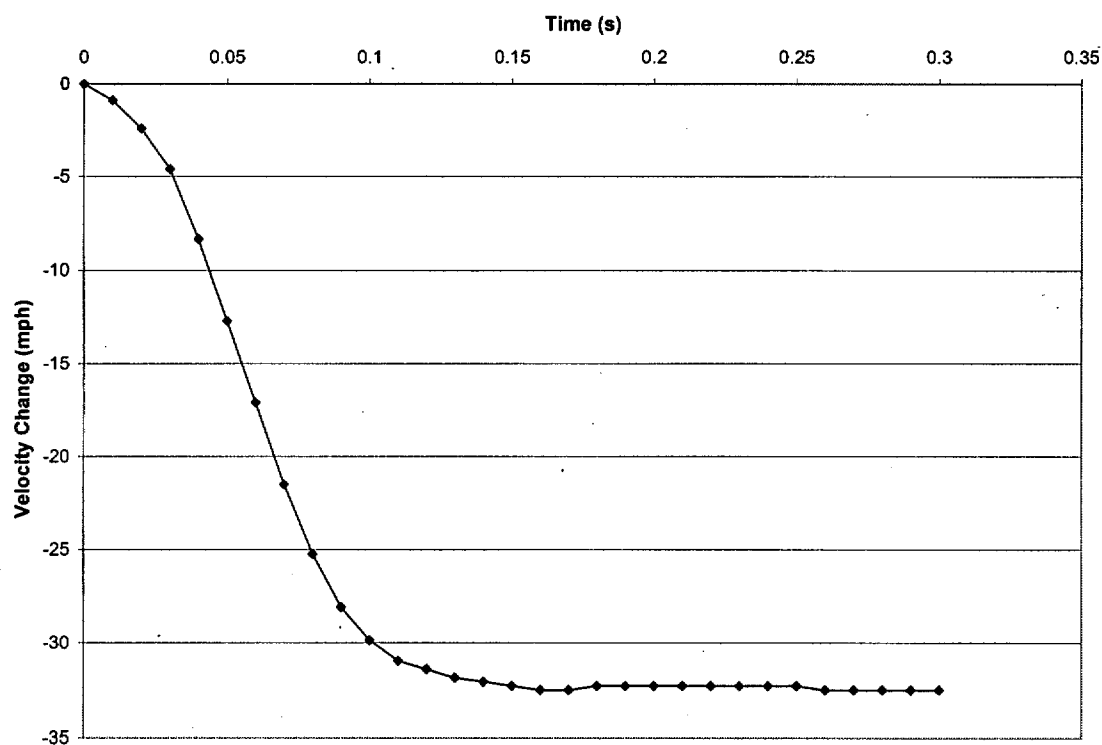


Figure 12. GM EDR Longitudinal Velocity Profile: 1999 Chevrolet Cavalier

2.1.3 The Ford EDR

More recently, Ford has publicly released information regarding its restraint control module (RCM), the Ford version of the EDR. The Ford RCM is designed to monitor the operation of the advanced restraints including seat belt pretensioners and dual-stage airbag inflators [37]. In contrast to the GM SDM, the RCM lacks the capability to record information prior to the collision event [34]. Also, the RCM only stores information for one event: a deployment or non-deployment event [33]. Similar to the GM SDM, however, the stored information can be accessed via the Vetronix CDR system [33].

Table 5 summarizes the data elements stored in the Ford RCM.

Table 5. Ford EDR Recorded Data Elements [34]

Parameter Type	Parameter	Data Type	Values
1. General	Data Validity Check	Coded	Valid/Invalid
	EDR Model Version	Integer	
2. Restraints	Safing Decision to Left (Driver) Side Bag Deployment [msec]	Integer	
	Safing Decision to Right (Passenger) Side Bag Deployment [msec]	Integer	
	Diagnostic Codes Active when Event Occurred	Integer	
	Algorithm Wakeup to Pretensioner [msec]	Integer	
	Algorithm Wakeup to 1 st Stage – Unbelted [msec]	Integer	
	Algorithm Wakeup to 1 st Stage – Belted [msec]	Integer	
	Algorithm Wakeup to 2 nd Stage –Belted [msec]	Integer	
	Driver Seat Belt	Coded	Engaged/Not Engaged
	Passenger Seat Belt	Coded	Engaged/Not Engaged
	Driver Seat Track in Forward Position	Coded	Yes/No
	Runtime [msec]	Integer	
	# Invalid Recording Times	Integer	
	Algorithm Wakeup to Driver Pretensioner Attempt [msec]	Integer	
	Algorithm Wakeup to Driver 1 st Stage Deployment Attempt [msec]	Integer	
	Algorithm Wakeup to Driver 2 nd Stage Deployment Attempt [msec]	Integer	
	Algorithm Wakeup to Passenger Pretensioner Attempt [msec]	Integer	
	Algorithm Wakeup to Passenger 1 st Stage Deployment Attempt [msec]	Integer	
	Algorithm Wakeup to Passenger 2 nd Stage Deployment Attempt [msec]	Integer	
3. Crash Pulse	Longitudinal (X-axis) Acceleration	Floating Point Array	
	Lateral (Y-axis) Acceleration	Floating Point Array	

Although the Ford RCM lacks the ability to record information prior to a collision, the data recorded during the collision event is more detailed than that of the GM SDM. Both vehicle acceleration and velocity are recorded in the longitudinal and lateral directions [34]. Also, the RCM records both parameters in 2-millisecond intervals, in contrast to the coarse 10-millisecond intervals of the GM SDM [33]. Due to this higher recording frequency, though, the RCM is only able to record for approximately 80 milliseconds [34]. Figure 13 and Figure 14 are plots of the RCM acceleration and velocity information in the longitudinal and lateral directions, respectively, for a 2000 Ford Taurus colliding with a tree.

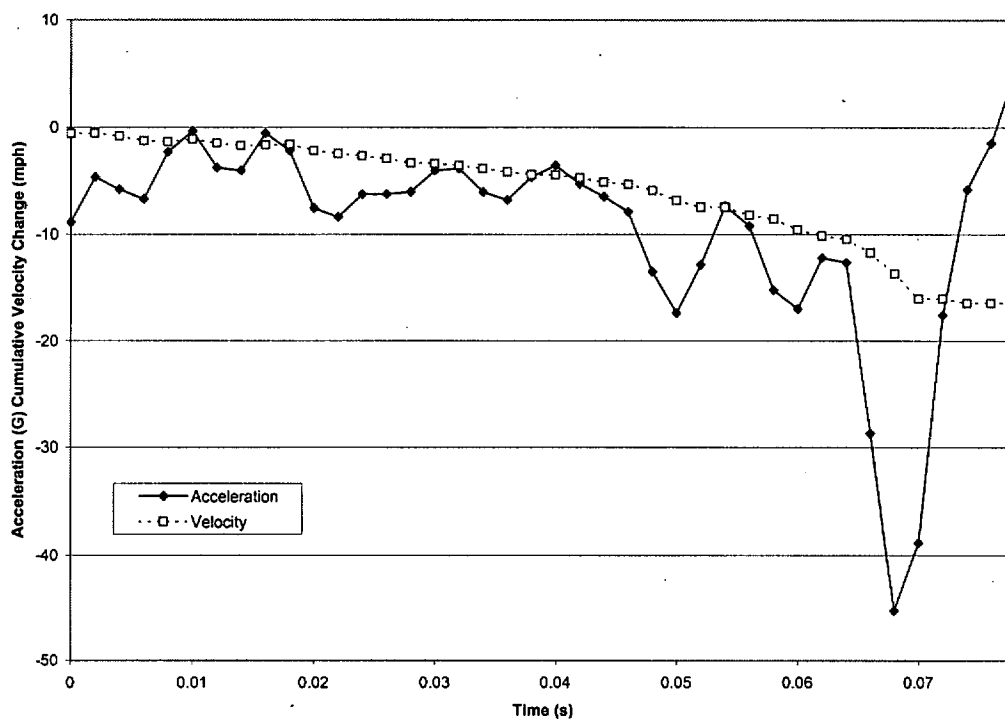


Figure 13. Ford RCM Longitudinal Acceleration and Velocity Information: 2000 Taurus

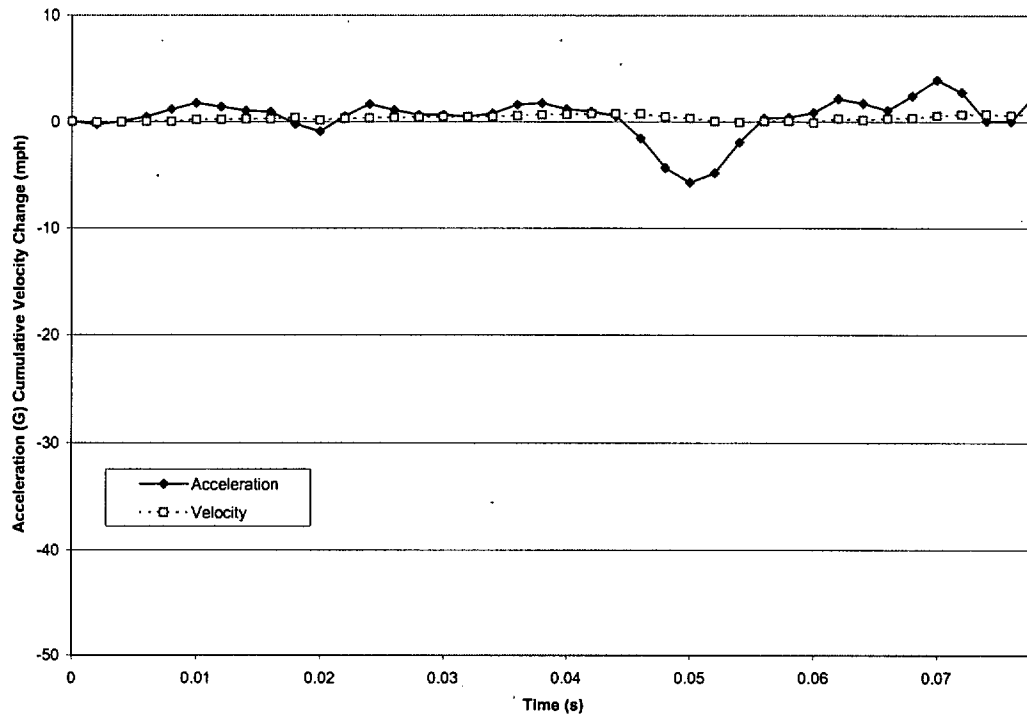


Figure 14. Ford RCM Lateral Acceleration and Velocity Information: 2000 Taurus

2.2 Rowan University EDR Database

Under sponsorship of the National Highway Traffic Safety Administration (NHTSA), Rowan University is in the process of developing a first-of-a-kind database of EDR data collected from traffic collisions in the United States [33,38,39]. Currently, the database consists of EDR data for over five hundred (500) cases collected between 1999 and 2002. Although a majority of the cases are GM vehicles, there are a small number of Ford cases in the database. The EDR data available for each case is consistent with the recording capabilities of the GM SDM or Ford RCM, as described previously. Reference Gabler and Hampton [38] or Clayton [33] for additional information regarding the format Rowan University Database.

As the EDR data was collected in conjunction with a particular accident investigation, each EDR case includes detailed information about the crash not available

from the EDR (e.g. type and severity of occupant injury). This corresponding information has been obtained through one of the following three accident investigation programs: the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS), NHTSA's Special Crash Investigations (SCI), and the Crash Injury Research and Engineering Network (CIREN). A brief description of each is provided below.

2.2.1 NASS and the Crashworthiness Data System

Started in 1979, NASS is the means by which the National Highway Traffic Safety Administration (NHTSA) collects data on automotive crashes in the United States. Providing data to researchers concerned with automotive and highway safety, NASS consists of two parts: the General Estimates System (NASS/GES) and the Crashworthiness Data System (NASS/CDS) [40]. NASS/GES is a nationally representative sample of all police-reported motor vehicle accidents in the United States [41]. NASS/CDS provides a more detailed record of approximately 5,000 crashes investigated each year [40]. The NASS/CDS database includes a random sample of minor, serious and fatal crashes involving cars, light trucks, vans and sport utility vehicles. A majority of the cases in the Rowan University Database include information collected in combination with the NASS/CDS program.

2.2.2 NHTSA Special Crash Investigations

NHTSA initiated the Special Crash Investigations (SCI) program in 1972 to provide a mechanism of investigating the effectiveness of the rapidly evolving vehicle technologies [42]. Focus areas of this program include side airbag performance, seat belt

performance, and child safety restraint performance [43]. The SCI program provides the most in-depth accident data available from NHTSA and typically includes approximately 100 cases per year [42]. Although not a nationally representative sample, the anecdotal cases support a detailed engineering analysis aimed at the improvement of the state-of-the-art vehicle safety systems. Approximately forty cases in the Rowan University Database have been collected in conjunction with the SCI program.

2.2.3 Crash Injury Research and Engineering Network

CIREN is a network of ten trauma centers across the United States that collects detailed information for approximately 400 crashes a year [38]. The intent is to allow NHTSA, safety engineers, the automotive industry, and medical professionals to jointly study serious occupant injury in an effort to improve the prevention, treatment and rehabilitation of these injuries [44]. Unlike the other databases that consider each documented accident a separate case, each vehicle occupant is considered a separate case in CIREN [45]. Data collected includes approximately 250 medical elements and approximately 650 elements related to the crash [45]. Approximately twenty cases in the Rowan University Database have been collected in conjunction with the CIREN program.

CHAPTER 3 – OBJECTIVE AND METHODOLOGY

3.1 Objective

The previously tenuous correlation to occupant injury coupled with fleet changes since the inception of the flail space model raise serious questions regarding its current applicability and demonstrates the necessity for a reassessment of the model. The purpose of this study is to develop and implement a methodology to investigate the correlation between the flail space model and injury to airbag-restrained occupants using EDR data. Since the flail space model depends on both the occupant impact velocity and occupant ridedown acceleration for the determination of injury potential, each will be examined independently prior to the assessment of the combination. Using the EDR velocity data in conjunction with detailed occupant injury information, the occupant impact velocity, occupant ridedown acceleration, and the combination will be evaluated based on the ability to predict maximum occupant injury severity as well as occupant injury severity for particular body regions. Also, confounding factors such as occupant belt usage will be examined based on their effect on trends in actual occupant injury.

3.2 Importance

Ultimately, a better understanding of how the flail space model correlates with actual occupant injury will promote more confidence in design and testing procedures for roadside safety hardware and potentially increase the effectiveness of these devices. In conjunction with the structural adequacy and post-impact vehicle trajectory requirements set forth in NCHRP Report 350 [10], the flail space model is used to determine the

acceptance of roadside safety hardware devices utilized in the United States. If this model was not at least generally indicative of actual occupant injury, there is a possibility that the decisions to accept or reject a particular piece of roadside hardware could be erroneous. In addition, design changes to roadside hardware are often based on the measured or simulated crash test criteria (i.e. a lower occupant injury potential as prescribed by the flail space model is assumed to provide a safer design). If there is no relation between the flail space model and occupant injury, design changes to hardware could result in increased costs with no additional safety benefit. Council and Stewart [27] also expressed these concerns in their previous attempt to characterize the relationship between occupant injury criteria and actual occupant injury.

This study also demonstrates the applicability of EDR data to vehicle and roadside safety research. Previous studies [27,28] attempting to establish a link between the flail space model and occupant injury lacked detailed information pertaining to the vehicle crash conditions (e.g. acceleration as a function of time). EDRs provide a coarse version of this vital information for real-world collisions. A benefit of this study is the development of a methodology for applying this data to characterize the correlation between the flail space model and occupant injury. From a broader perspective, use of EDR data could significantly enhance understanding of human injury tolerance relationships. Human subjects are not used in full-scale crash tests to determine these relationships due to obvious moral and legal implications. EDRs, however, provide information about a real-world collision that is similar to that recorded in a full-scale, instrumented crash test. In essence, the scenario replicates the use a human subject in a

full-scale crash test; an invaluable circumstance for the vehicle and roadside safety research community.

3.3 Methodology

3.3.1 Overall Methodology

As shown in Figure 15, the general methodology of this investigation is a comparison between the occupant injury potential (predicted using the flail space model) and the actual injuries attained in the real-world collision. The GM EDR velocity information will be utilized to compute the occupant impact velocity and occupant ridedown acceleration as specified by the flail space model. Using the corresponding accident investigation information, the actual occupant injury severity values are compared to the computed flail space model criteria both graphically and statistically.

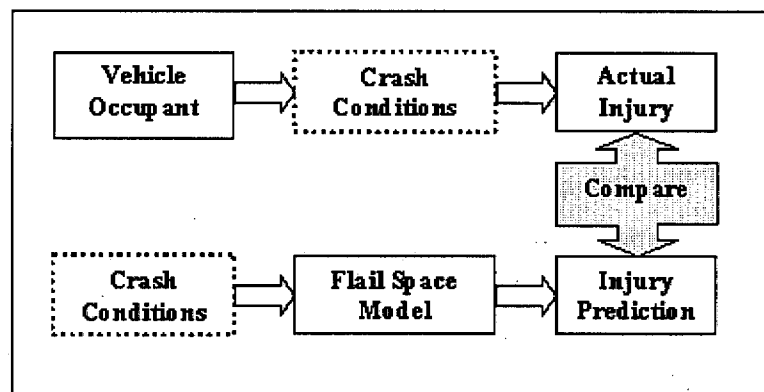


Figure 15. Overall Methodology Schematic

An attempt has been made to utilize both the GM and Ford data available in the Rowan University EDR Database, however, the subsequent analysis focuses solely on the available GM EDR cases. The Ford data available in the database is limited to ten (10) cases, all of which have lower occupant injury severity. In addition, the Ford EDR is only capable of recording crash pulse information for a maximum of eighty (80)

milliseconds, typically not a sufficient duration to capture an entire collision event. Due to the inadequate number of cases coupled with the Ford EDRs recording duration restriction, the available Ford cases have been excluded from the analysis.

3.3.2 Case Selection

The Rowan EDR database was first searched to identify those GM EDR cases suitable for analysis. Suitable cases adhere to the following criteria:

1. Airbag deployment
2. Complete GM EDR velocity data as a function of time
3. Known injury data for either the left or right front seat occupant
4. Frontal collision with no vehicle rollover

In an attempt to utilize cases that have a higher potential for occupant injury, the data was narrowed to include only deployment events. An analysis of the cases with higher injury severity values will allow for an assessment of the validity of the flail space model threshold values. Recall that the original intent of these threshold values is to prevent a majority of serious and fatal injuries. With respect to the AIS scale, an occupant subjected to the threshold occupant impact velocity and/or occupant ridedown acceleration would, in theory, attain a maximum injury of AIS 3 [9]. If the data set is void of higher severity injuries, however, an investigation of these presumptions is not possible. Although the lower severity injuries are important to the overall correlation with respect to the flail space model, the higher severity injuries are essential to this study.

To facilitate the computation of the occupant impact velocity and the occupant ridedown acceleration, EDR velocity versus time information for the collision must be

available. An additional stipulation for this restricted data set is that the recorded velocity profile is “complete” or converges to a constant velocity value. Since the occupant ridedown acceleration is dependent on the vehicle accelerations later in the collision event (after occupant-interior impact), a “complete” pulse is necessary to ensure a valid ridedown acceleration value. Incomplete pulses could also lead to erroneous computation of the occupant impact velocity in the case where the occupant displaces a distance less than either prescribed flail space limit. In these cases, the impact velocity is set equal to the total change in vehicle velocity, which is not known with certainty if the pulse is not “complete”.

To facilitate an analysis of the flail space model, occupant injury information must be available from the corresponding accident data. Note that the injury information must pertain to an occupant situated in the front row of seats in the vehicle. The flail space model only provides an indication of injury potential for front seat occupants, as this is typically the worst-case scenario [12]. In contrast to redirection collisions where only the nearside occupant is considered critical by the flail space model, both front seat occupants can be considered in this analysis since the data set is limited to frontal collisions. Because the forces are primarily longitudinal, there is negligible variation in the deceleration experienced by either front seat occupant in the frontal collision mode.

The data set is limited to the frontal collision subset of suitable cases since the GM EDR records velocity information only in the longitudinal direction (parallel to the typical direction of travel). Any collision with a substantial lateral change in velocity will have little or no impact on the longitudinal velocity but could produce significant occupant injury. In this case, any correlation between the longitudinal flail space model

and occupant injury would be invalid. A frontal collision is defined with the use of the NASS variables general area of damage (GAD) and principal direction of force (PDOF). GAD describes the location of the damage to a vehicle involved in a collision while PDOF is an estimate of the direction of the largest force involved in the most harmful event of a collision (0 - 359 degrees) with respect to the impact point. For the purpose of this study, a frontal collision is defined by a GAD corresponding to the front of the vehicle and a PDOF of 0 degrees plus or minus 10 degrees (see Figure 16). Since the flail space model assumes that the vehicle remains upright, all collisions involving vehicle rollover have been omitted from the suitable data set.

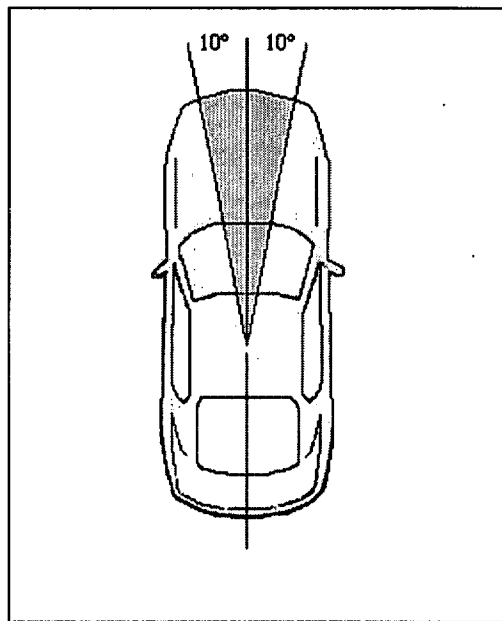


Figure 16. PDOF Variation of Included Full Frontal Collisions

Although the flail space model is designed for impacts with roadside hardware devices, there has been no attempt to limit the cases based on the object struck. As such, the final data set includes both vehicle-to-fixed object and vehicle-to-vehicle collisions. If there is indeed a relationship between the flail space model and injury severity, it

should be as equally relevant to vehicle-to-vehicle crashes as to vehicle-to-fixed object crashes.

Based on the enumerated restrictions, the frontal collision deployment data set extracted from the Rowan EDR Database consists of a total of 112 cases (91 left front seat occupants and 21 right front seat occupants). Figure 17 through Figure 19 provide information regarding the cases in the frontal deployment data set. The distribution of object struck is illustrated in Figure 17; note that the object struck corresponds to the most harmful event as determined by the accident investigators. An examination of this figure indicates that the data is split approximately sixty (60) percent vehicle-to-vehicle collisions and forty (40) percent vehicle-to-roadside object collisions. The category entitled “other” includes a bridge impact and two wall impacts. Figure 18 presents the distribution of vehicle model years for the vehicles in the frontal deployment data set. Model year 1999 vehicles represent the largest proportion (29%) while model year 1996 vehicles represent the smallest proportion (5%); the remaining data is uniformly dispersed among the rest of the model years. Figure 19 shows the distribution of vehicle type in the frontal deployment data set. The data set contains approximately seventy (70) percent car-type vehicles and thirty (30) percent light truck and van-type vehicles.

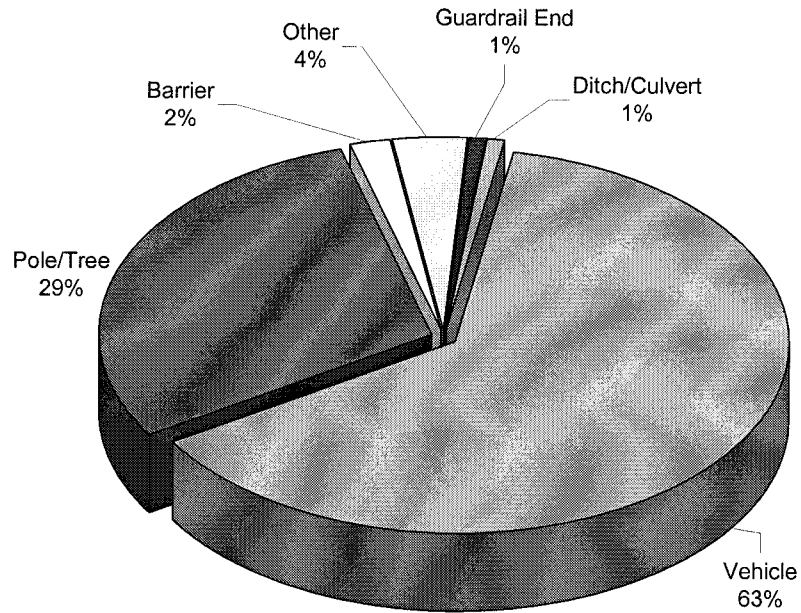


Figure 17. Object Struck Distribution for the Frontal Deployment Data Set

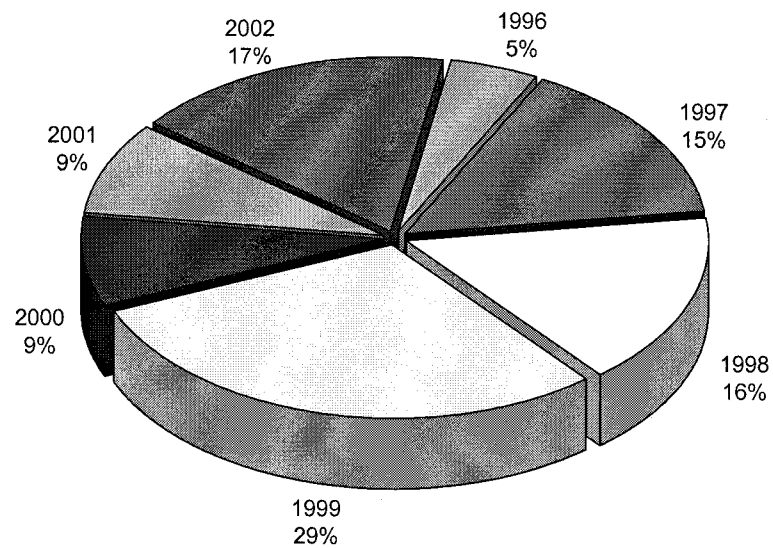


Figure 18. Distribution of Vehicle Model Year for the Frontal Deployment Data Set

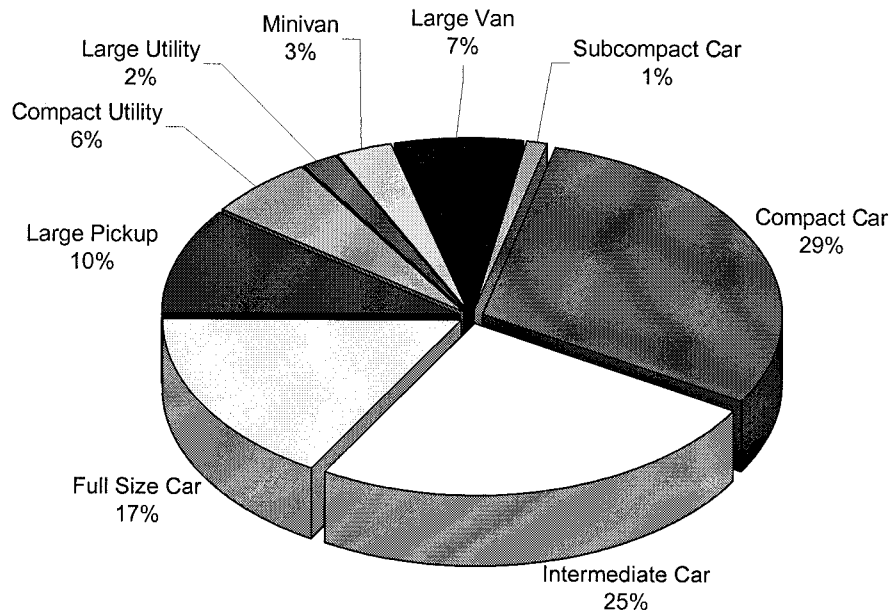


Figure 19. Distribution of Car Type for the Frontal Deployment Data Set

For a majority of the analysis, the frontal deployment data set is restricted further to include only single impact collisions. Since it is limited to recording information for a maximum of two impacts, the GM EDR will not capture all the events if a crash has more than two impacts. Restriction of the data set to only single event collisions also ensures that the EDR velocity data corresponds to the injury-producing event, thus, ensuring a valid comparison between the flail space criteria and the occupant injury. For the single event subset of the frontal deployment data set, there are a total of 69 cases (55 left front seat occupants and 14 right front seat occupants). Figure 20, Figure 21, and Figure 22 present the distribution of the most harmful object struck, vehicle model year, and vehicle type, respectively, for the single event frontal deployment data set. In comparison to the frontal data set, the restricted data set has a higher occurrence of vehicle-to-vehicle collisions (78% compared to 63%). For the distribution of vehicle model year, the

percentages are approximately equivalent between the data sets. Similarly, there are some small differences in vehicle type percentages between the data sets, but overall they are approximately equivalent.

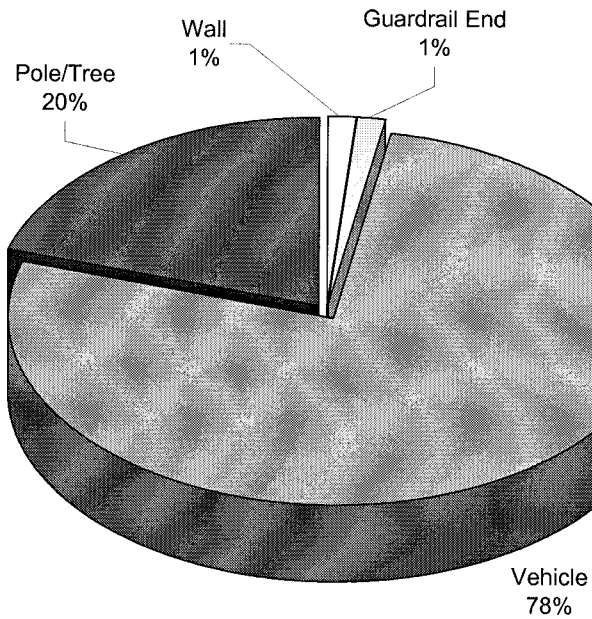


Figure 20. Distribution of Object Struck for the Single Event Frontal Deployment Data Set

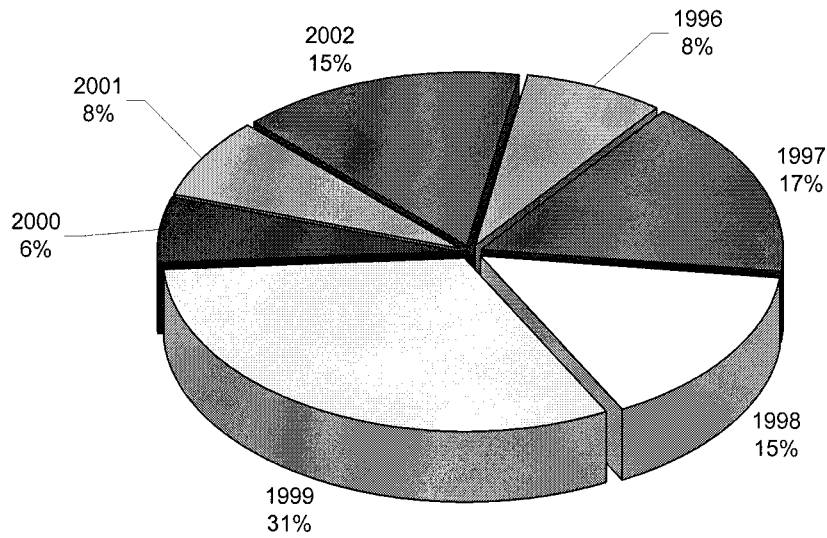


Figure 21. Distribution of Vehicle Model Year for the Single Event Frontal Deployment Data Set

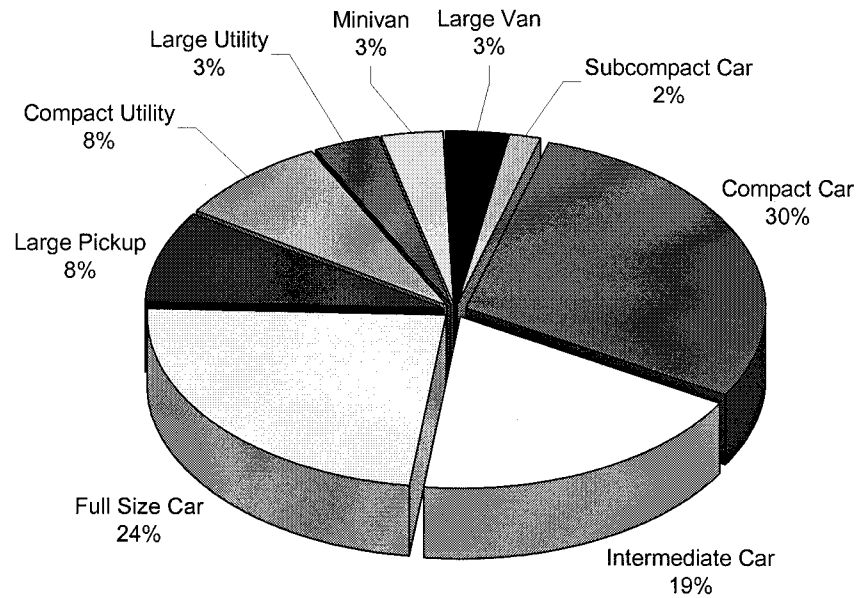


Figure 22. Distribution of Car Type for the Single Event Frontal Deployment Data Set

3.3.3 Calculation of the Occupant Impact Velocity

Utilizing the Microsoft® EXCEL program, the following procedure was used to determine the longitudinal occupant impact velocity for the suitable cases in the EDR database:

- 1) Convert GM EDR velocity data from English to metric units (mph to m/s).
Reference Figure 23.
- 2) Numerically integrate the longitudinal EDR relative velocity data using the trapezoidal method to obtain occupant relative position as a function of time.
Reference Figure 24.
- 3) Interpolate to determine the time at which the occupant impacts the interior (relative distance = 0.6 meters). Reference Figure 25.
- 4) Use the occupant impact time and the EDR relative velocity data to obtain the longitudinal V_I . Reference Figure 26.
- 5) For cases where the theoretical occupant does not exceed the longitudinal flail space limit, V_I is set to the maximum velocity change of the vehicle (as recorded by the EDR).

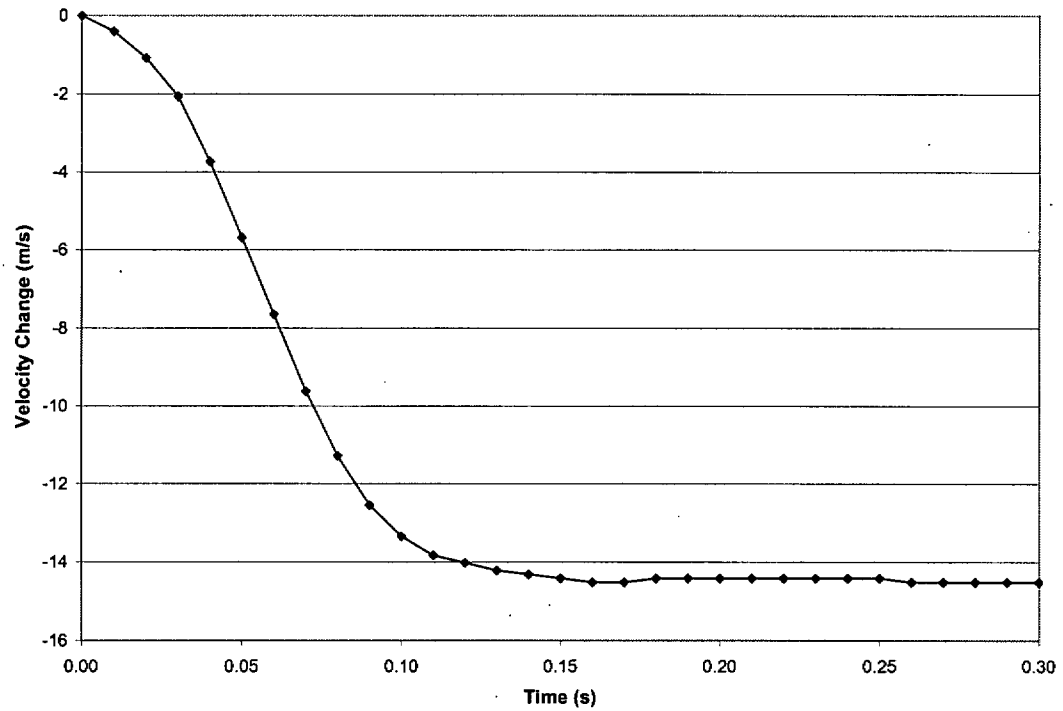


Figure 23. Longitudinal Velocity Change Profile (Metric Units)

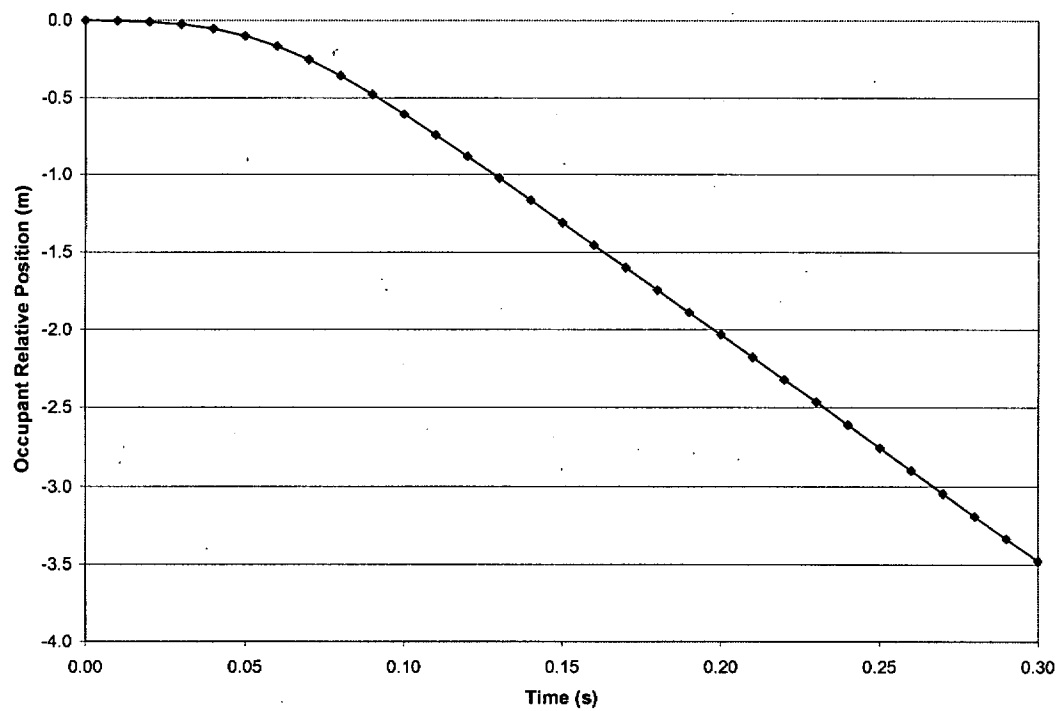


Figure 24. Occupant Relative Position as a Function of Time

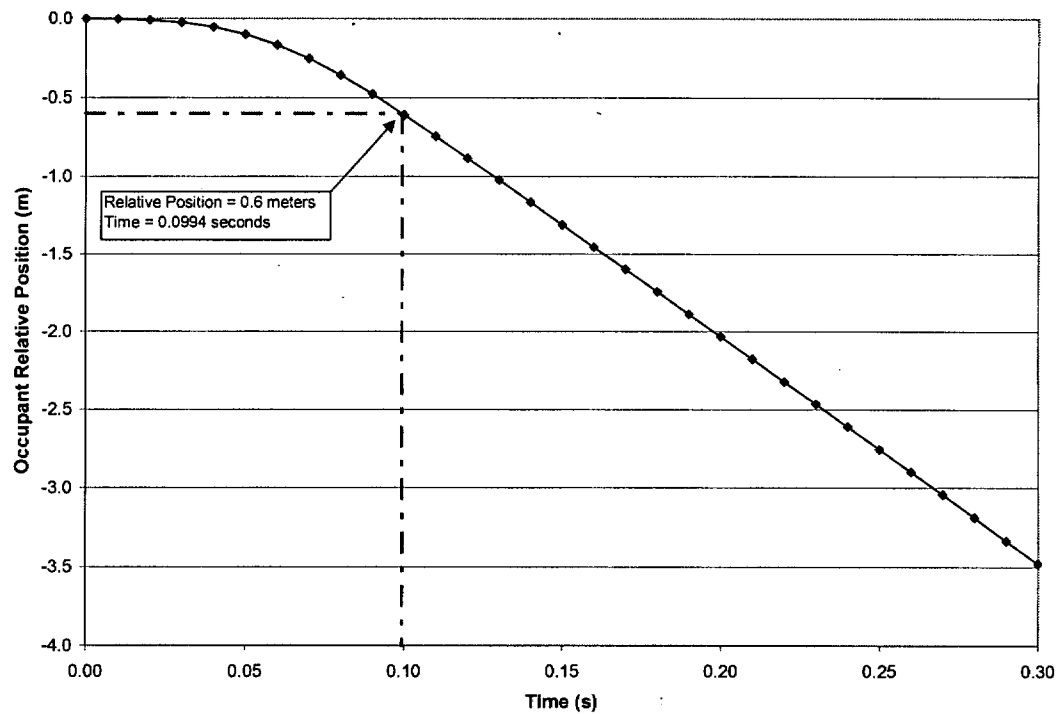


Figure 25. Interpolation to Find Time to Occupant Impact

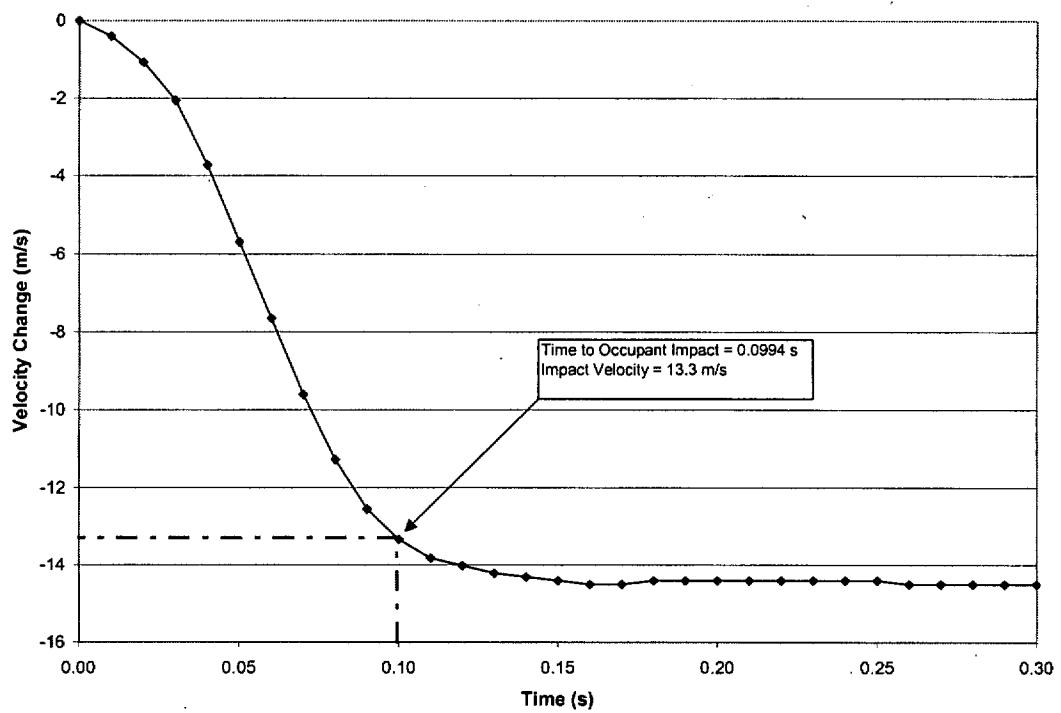


Figure 26. Occupant Impact Velocity Determination

To be consistent with NCHRP Report 350, the velocity (in miles per hour) provided by the GM EDR has been converted to meters per second. Note that the GM EDR measures the relative change in velocity from inside the vehicle's occupant compartment rather than the absolute change in velocity (e.g. with respect to the ground). This is analogous to measuring the change in velocity of the steering wheel (i.e. the occupant compartment) towards an unrestrained vehicle occupant. Likewise, integration of the GM EDR data results in the relative position of an unrestrained occupant with respect to the occupant compartment with respect to time. Using the longitudinal "flail space" limit of 0.6 meters prescribed by NCHRP Report 350, the theoretical time for the unrestrained occupant to impact the vehicle interior is determined by interpolation of the relative position versus time data. Since EDR velocity represents the difference in velocity between an unrestrained occupant and the vehicle occupant compartment at any point in time, the occupant impact velocity at the theoretical time of occupant impact with the vehicle interior can be interpolated directly from this data.

For cases where the occupant does not reach the flail space limit, NCHRP 350 specifies that V_I should be equal to the vehicle's change in velocity that occurs during contact with the test article. The maximum change in vehicle velocity recorded by the EDR is assumed to provide an estimate of this quantity. For example, assume a vehicle collides head-on with a breakaway sign support and the deceleration of the vehicle is not sufficient to propel an unrestrained occupant forward 0.6 meters. Assuming the EDR records a maximum vehicle velocity change of 5 m/s, the occupant impact velocity is assumed to be 5 m/s in this instance. For the frontal deployment data set and single event frontal deployment data set, there are a total of twenty-three (23) and eleven (11) cases,

respectively, that fall into this category. These instances represent a total of twenty-one (21) percent of the frontal deployment data set and approximately sixteen (16) percent of the single event frontal deployment data set.

Figure 27 presents the distribution of occupant impact velocity for both the frontal deployment and single event frontal deployment data sets. Despite having a significantly smaller number of cases, the distribution of the occupant impact velocity for the single event frontal deployment data set appears similar to that of the frontal deployment data set. Note, for both data sets, that a significant number of the available cases (approximately 80% in each data set) have occupant impact velocity values less than the current NCHRP 350 longitudinal threshold of 12 m/s. The lack of values in excess of the thresholds may inhibit the ability of these data sets to evaluate the appropriateness of the flail space model.

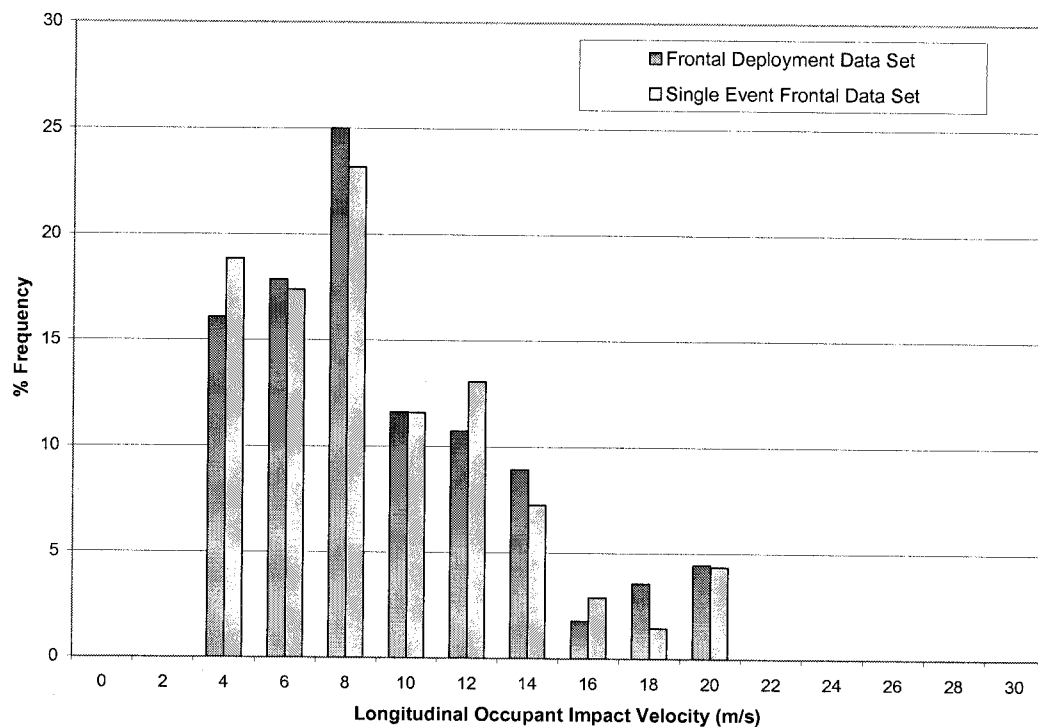


Figure 27. Distribution of Longitudinal Occupant Impact Velocity

3.3.4 Calculation of the Occupant Ridedown Acceleration

Also utilizing the Microsoft® EXCEL program, the following procedure was used to determine the longitudinal occupant ridedown acceleration for the suitable cases in the EDR database:

- 1) Using the GM EDR longitudinal velocity information (Figure 28), obtain vehicle accelerations by numerical forward differentiation. Convert values from meters per second squared to G's. Reference Figure 29.
- 2) After the time of occupant impact, choose the largest absolute acceleration value as the occupant ridedown acceleration. Reference Figure 30.
- 3) If the occupant does not reach the longitudinal flail space limit or there is no recorded velocity information after the time of occupant impact, a value for the ridedown acceleration is not assigned.

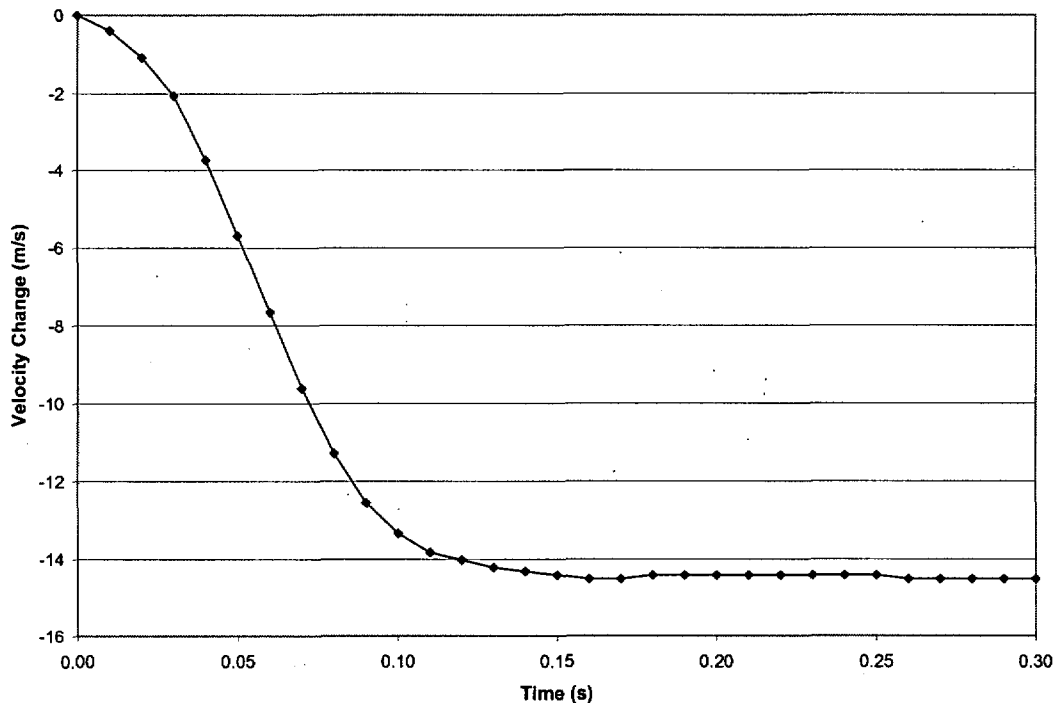


Figure 28. Longitudinal Velocity Change Profile

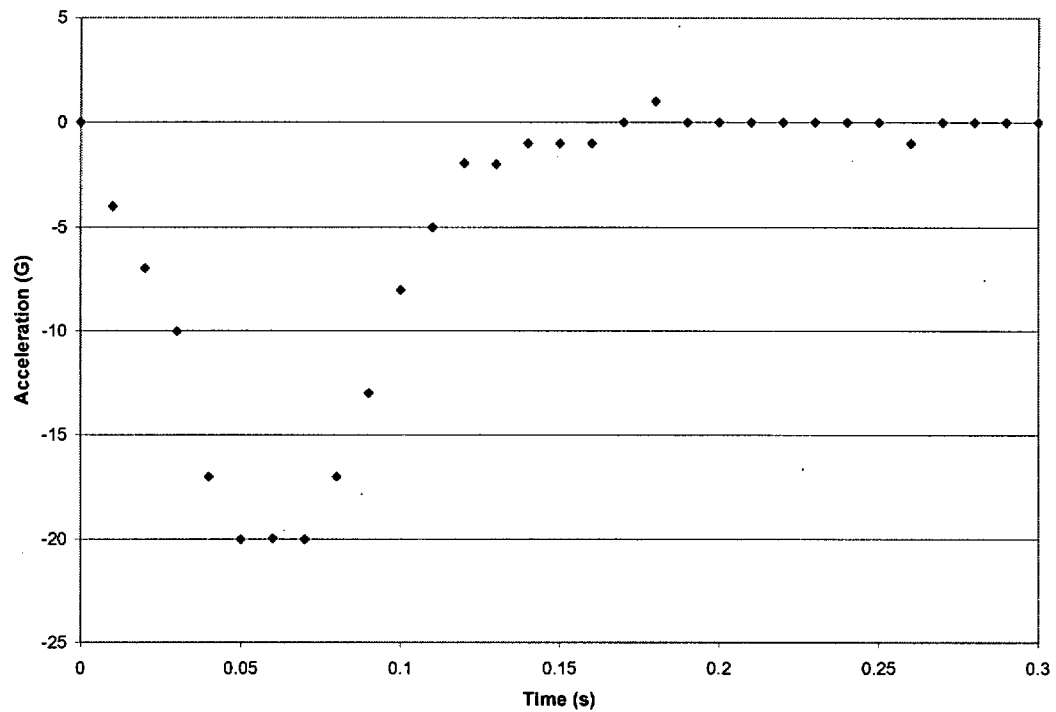


Figure 29. Longitudinal Acceleration as a Function of Time

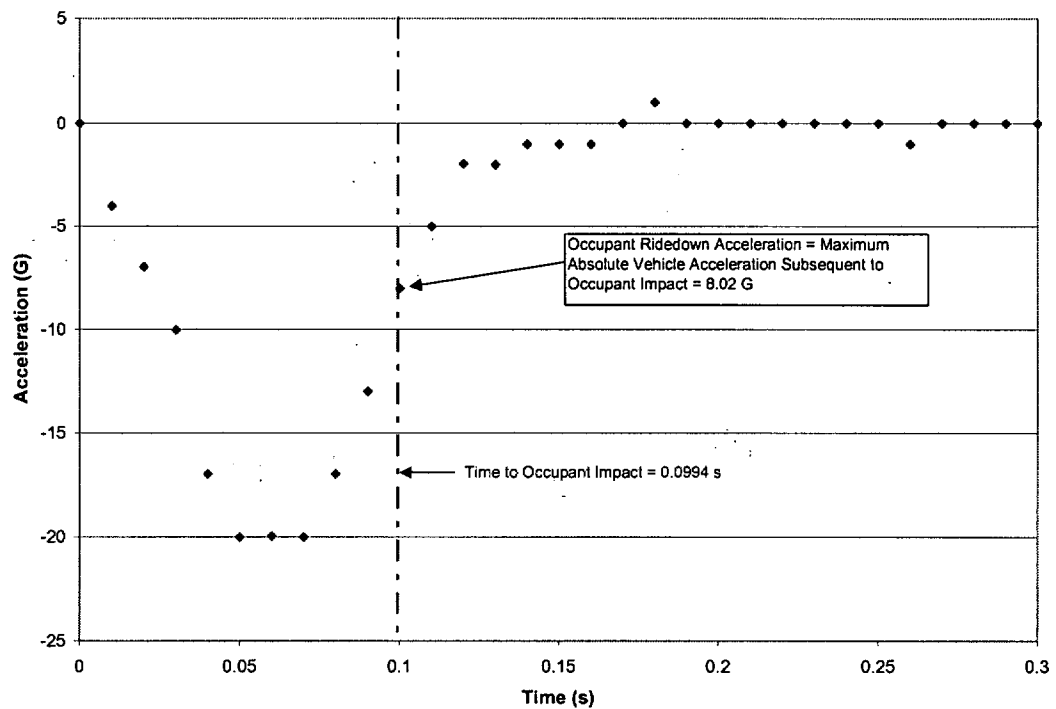


Figure 30. Occupant Ridedown Acceleration Determination

Since the GM EDR only records the velocity profile, a derivative must be utilized to obtain the acceleration information required for the calculation of the occupant ridedown acceleration. The estimation of the continuous velocity function with discrete points, however, results in degraded information regarding the slope, or acceleration, of the sampled function. Further complications arise from the relatively coarse GM EDR recording interval of once every ten (10) milliseconds. NCHRP Report 350 specifies that the occupant ridedown acceleration is the largest 10-ms moving average of the vehicle accelerations subsequent to the time of occupant impact with the interior. To provide some coarse estimate of this quantity, however, the acceleration values determined every 10-ms from the velocity data are assumed to be the 10-ms averages required by NCHRP Report 350. The acceleration values are then converted to G's since the occupant ridedown acceleration threshold values are in these units.

Note that if the time to occupant impact with the interior occurs between two EDR sample times, the determination of the occupant ridedown acceleration begins at the earlier point in time. NCHRP 350 guidelines mention a similar procedure of including acceleration information prior to the time of theoretical occupant impact if there is a spike in acceleration present [10]. Also, for the cases where the occupant impact is just prior to the termination of the GM EDR velocity information, no value is computed for the occupant ridedown acceleration. A minimum of two velocity points is required to produce an estimate of this parameter. Similarly, in the case where the occupant does not reach the longitudinal flail space threshold, a value of zero (0) is assigned to the occupant ridedown acceleration. Since the theoretical occupant does not contact the vehicle

interior, the occupant does not experience any acceleration according to the flail space model.

Figure 31 illustrates the distribution of the longitudinal occupant ridedown acceleration for both the data sets. Similar to the distribution of the occupant impact velocity, the distribution of the occupant ridedown acceleration for the smaller single event frontal deployment data set appears similar to that of the larger frontal deployment data set. Again, a significant number of the available cases have occupant ridedown accelerations below the NCHRP 350 limits, which may inhibit the ability of these data sets to evaluate the appropriateness of the flail space model.

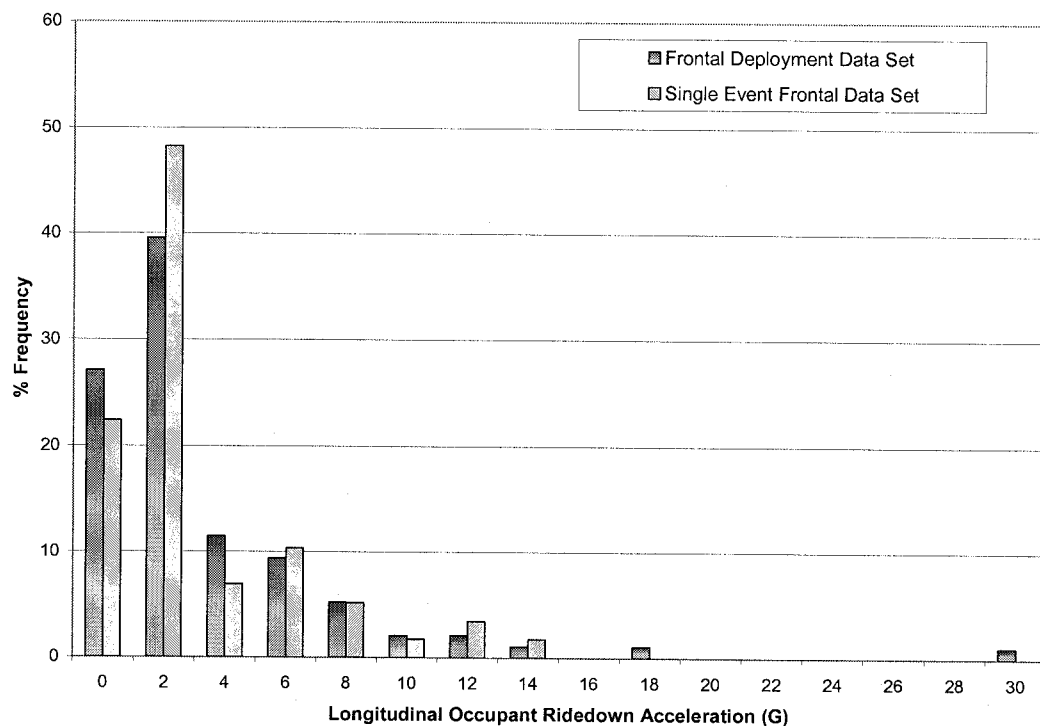


Figure 31. Distribution of Longitudinal Occupant Ridedown Acceleration

3.3.5 Quantification of Injury

For the quantification of occupant injury, the Abbreviated Injury Scale (AIS) is used for this study. Under the joint sponsorship of the Society of Automotive Engineers

(SAE), the American Medical Association (AMA), and the Association for the Advancement of Automotive Medicine (AAAM), this procedure was developed in the early 1970's to provide a standardized system of classifying injury type and severity for accident investigators [46]. The AIS scale is a numerical method to describe injury severity in terms of threat to life. Note that this scale is anatomically based resulting in only a single AIS score for each injury attained by an individual. Frequently, the maximum of these individual scores, also known as the maximum AIS value or MAIS value, is used as a gauge of overall severity of occupant injury. Table 6 illustrates the levels of occupant injury used in the AIS scale [46]. Although the presence of only six injury categories suggests a qualitative scale, the AIS scale is excruciatingly detailed and quantitative. For instance, a laceration to the skin in the chest area is considered AIS 2 if it is greater than 20 cm in length and includes subcutaneous tissue; to qualify as AIS 3, the same laceration must produce a blood loss of at least twenty (20) percent by volume.

Table 6. The Abbreviated Injury Scale

AIS Value	Injury Severity
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum/Fatal

The accident data, collected in parallel with the EDR data, rates the severity of each occupant injury using this scale. For this study, the MAIS values will be used as an indicator of overall injury severity while the individual AIS values will be utilized to investigate occupant injury by body region. Note Michie indicates that the flail space

model thresholds are intended to correspond to the transition between an AIS 3 and AIS 4 injury severity [12].

3.3.6 NCAP Comparison

As the GM EDR does not directly provide the vehicle acceleration measurements required by NCHRP Report 350 [10] for the calculation of the flail space model criteria, a modified version of these procedures, outlined in section 3.3.4, is used for this study. To investigate how these modifications affect the values of the occupant impact velocity and the occupant ridedown acceleration, six (6) NCAP tests were analyzed. Each NCAP test had GM EDR data in conjunction with the typical acceleration data specified by SAE J211 [4], a standard for the collection of data for crash tests. Note that NCHRP Report 350 also specifies this automotive standard for use with full-scale roadside hardware crash tests.

The occupant impact velocity and occupant ridedown acceleration were computed using the EDR data and the procedures outlined in sections 3.3.3 and 3.3.4, respectively. These values were then compared to the occupant impact velocity and occupant ridedown accelerations obtained using the more precise crash test accelerometer information and the procedures outline in NCHRP Report 350. Results of the comparison for the occupant impact velocity and occupant ridedown are summarized in Table 7.

Table 7. NCAP and EDR Comparison Results

NCAP Test Designation	Occupant Impact Velocity			Occupant Ridedown Acceleration		
	NCAP (m/s)	EDR (m/s)	Error (%)	NCAP (G)	EDR (G)	Error (%)
4487	16.86	16.34	3.1	13.77	13.99	1.6
4472	15.12	14.40	4.8	11.98	16.96	41.6
4244	15.79	15.17	3.9	6.89	9.89	43.5
4198	17.16	16.25	5.3	6.51	10.99	68.7
3952	17.12	16.95	1.0	8.88	15.00	68.9
3851	15.27	15.60	2.2	10.88	11.99	10.2

Comparing the occupant impact values in the six (6) tests, the average error for the EDR-determined occupant impact velocity was 4 percent (6% maximum). For the occupant ridedown acceleration, the EDR consistently overestimated the value on average by 40 percent with an overall range between 2 and 68 percent. Although the calculation of the occupant impact velocity is within reasonable tolerances of the actual value, the computation of the occupant ridedown acceleration provides only an upper bound on the actual value. Refer to Appendix B for additional information and graphical comparisons of the NCAP and GM EDR velocity and acceleration information for each test.

CHAPTER 4 – ANALYSIS

4.1 Occupant Impact Velocity as a Predictor of Injury

4.1.1 Maximum Occupant Injury

To investigate the efficacy of occupant impact velocity as a predictor of injury, the maximum abbreviated injury scale (MAIS) values are plotted as a function of longitudinal occupant impact velocity. Figure 32 is a plot for all the airbag deployment frontal collision cases in the database, which total 112 (91 left front seat occupants and 21 right front seat occupants). Note that the total is not a count of the number of vehicles exposed to collision events in the database, as some vehicles may contain multiple occupants. For vehicles with multiple front seat occupants, each front seat occupant represents a separate analysis case. As the flail space model estimates injury potential only for front seat occupants, only front seat occupants were considered in the analysis. For comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines.

According to the flail space model, injury severity should increase as the occupant impact velocity increases. As such, most points would be expected to fall within a diagonal band from the origin to the upper right corner of the plot. Also, if the current NCHRP 350 maximum longitudinal occupant impact velocity threshold limit of 12 m/s is valid, a majority of the more serious injuries ($\text{MAIS} \geq 3$) should occur at occupant impact velocities that exceed this limit. Although there are a few outliers, a majority of the data points follow the expected trend. Also, with the exception of a single case, all cases below the NCHRP 350 maximum occupant impact velocity threshold have a less

severe injury severity rating ($\text{MAIS} \leq 3$). Conversely, a majority of the cases in excess of the maximum NCHRP 350 threshold are of higher injury severity ($\text{MAIS} \geq 3$).

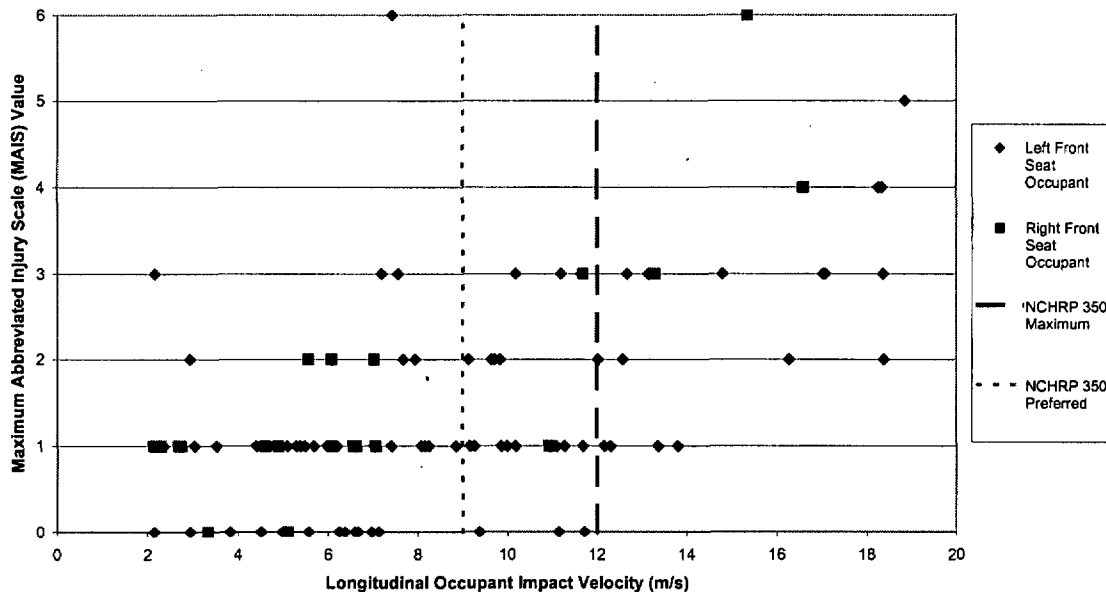


Figure 32. Occupant Impact Velocity and Maximum Occupant Injury In Frontal Deployment Collisions

Although a portion of the deviation from the expected trend can be attributed to confounding variables (e.g. occupant height and weight differences, injury tolerance differences, and occupant compartment differences), deviations may also result from the two event maximum data capturing capability of the GM EDR. Should a particular vehicular accident involve a single vehicle in more than two (2) collisions of sufficient severity to warrant data recording, the GM EDR will fail to record at least one of these collisions. To investigate how this limitation affects the scatter in Figure 32, the data must be grouped by number of events (i.e. collisions) for a particular vehicle involved in an accident. Figure 33 illustrates the maximum occupant injury as a function of longitudinal occupant impact velocity arranged by the number of events for a particular

vehicle. The number of events for a particular vehicle is obtained from the corresponding accident data.

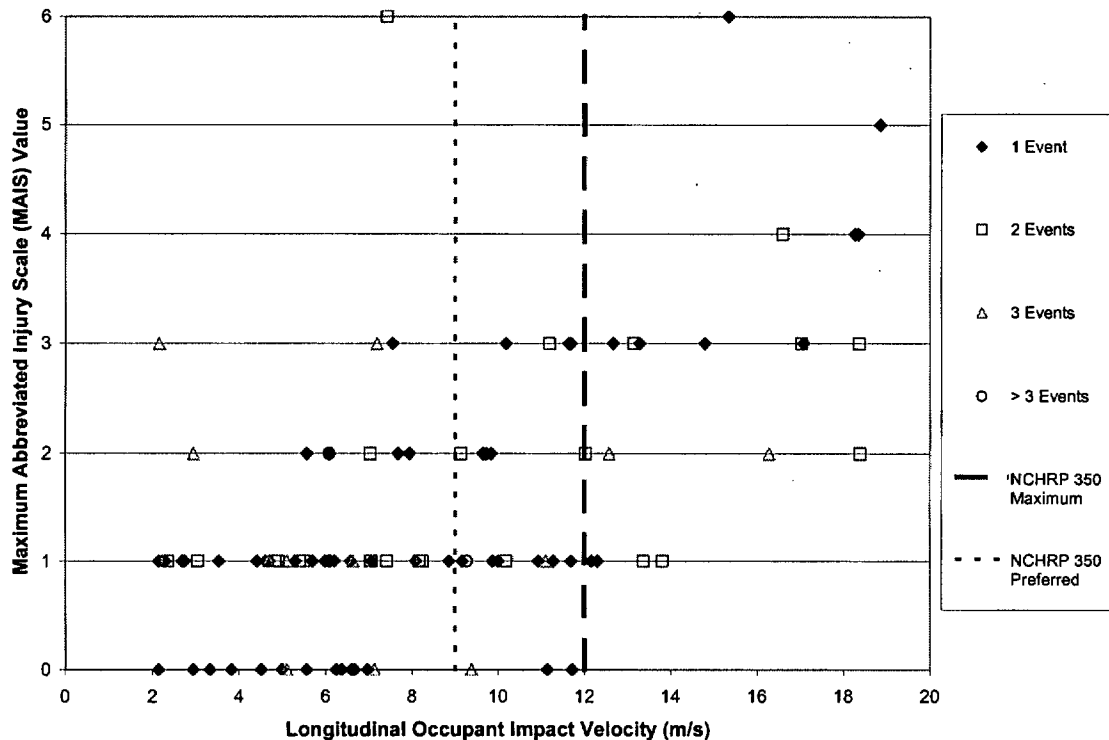


Figure 33. Occupant Impact Velocity and Maximum Occupant Injury In Frontal Deployment Collisions: Number of Events

Although there is a large amount of scatter in each event classification, the majority of the outliers are multiple event collisions. This appears reasonable since the EDR may or may not have captured the most harmful event in the collision. For instance, vehicle 'A' could strike vehicle 'B' in such a manner that the GM EDR (in vehicle 'A') records information for both non-deployment and deployment events for vehicle 'A'. Subsequent to striking the vehicle 'B', however, vehicle 'A' veers off the roadway comes to rest after striking a large tree. If the GM EDR does not have the deployment level recording capability (i.e. the non-deployment information from the first collision is write protected), the velocity information will not include the secondary collision with the tree.

In this case, if the collision with the large tree produced the resulting occupant injury, a comparison between this injury and EDR data would be meaningless.

Besides the potential for missing velocity data, the flail space model was not developed with the intent of estimating occupant injury in multi-event collisions. A typical full-scale crash test of roadside hardware involves only a single collision: the vehicle impacting the roadside feature. The rationale is that the initial collision has the highest potential for occupant injury since vehicle speeds are typically greatest [28]. Theoretically, an estimation of occupant injury for this case will provide the worst-case scenario in terms of occupant injury. For real world collisions with roadside hardware (particularly longitudinal barriers), however, research [46] indicates that secondary collisions appear to pose a more significant risk to occupants. There has been no evidence or research to investigate if this trend applies to the other collision modes (i.e. vehicle to vehicle) more prevalent in the Rowan University EDR database. Although these multi-event collisions are important in terms of a broad understanding of occupant injury in collisions, they fall outside of the predictive capability of the flail space model. Also, the intent of this research is to evaluate the efficacy of the flail space model at predicting occupant injury rather than assessing the effect of multiple collisions on occupant injury. The restriction to single event collisions will be more indicative of full-scale crash tests and will provide a certainty that the injury-producing event is captured by the EDR.

Figure 34 is a plot of maximum occupant injury in single event, frontal collisions only. This restricted data set is comprised of 69 total data points (55 left front seat occupants and 14 right front seat occupants).

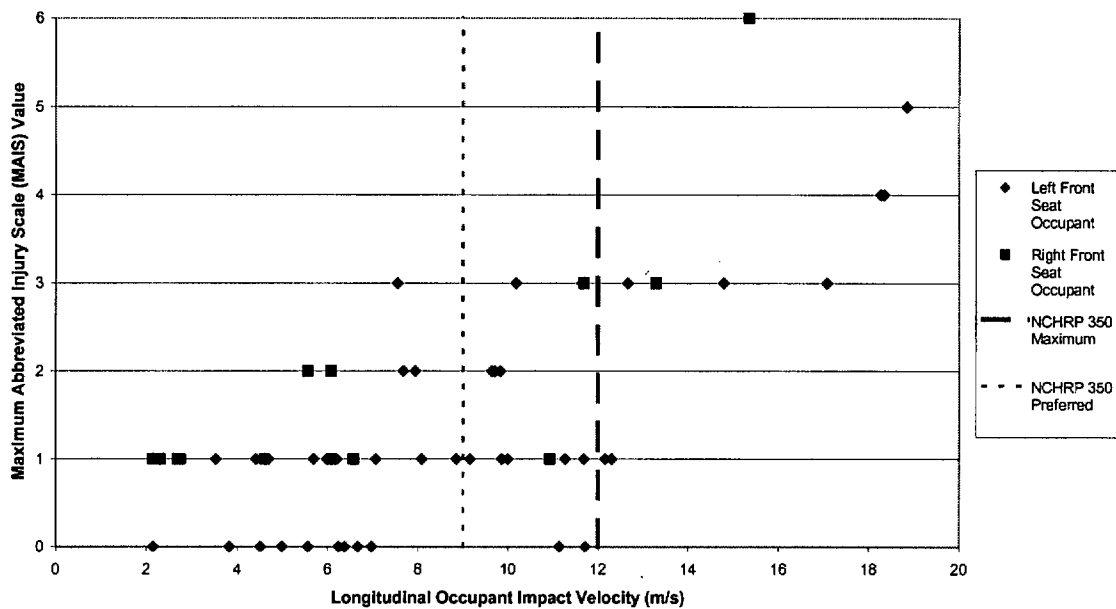


Figure 34. Occupant Impact Velocity: Maximum Occupant Injury In Single Event Frontal Collisions

As illustrated in Figure 34, the expected diagonal band is clearly evident without the scatter present in the previous plots. Also, the current maximum longitudinal occupant impact velocity threshold appears to be reasonable since the more severe injuries ($\text{MAIS} \geq 3$) occur at occupant impact velocities that exceed the threshold and the less severe injuries ($\text{MAIS} < 3$) occur at occupant impact velocities below the threshold. Both of these observations indicate that the occupant impact velocity is a good predictor of overall injury for single event, frontal collisions.

The flail space model was designed to predict injury potential for an unrestrained occupant, which is deemed the worst-case scenario. Ideally, the flail space model should provide the best estimate of injury for unbelted occupants. This prediction may be complicated, however, by the presence and deployment of airbags in the analyzed cases. If the current longitudinal occupant impact velocity thresholds are valid for an unrestrained occupant in a vehicle without an airbag, the values are expected to be

conservative for an unrestrained occupant in a vehicle with an airbag. To investigate this hypothesis, Figure 35 presents maximum occupant injury in single event, frontal deployment collisions as a function of longitudinal occupant impact velocity and seat belt status. Note that the belt status has been obtained from the corresponding accident investigation data (e.g. NASS/CDS, CIREN, or SCI). Although the GM EDR records belt status, there are disparities between the recorded belt status and belt usage as reported by the accident investigators. For the analysis that follows, the determination made by the accident investigator has been assumed to be accurate.

Figure 35 indicates that all belted occupants (51 cases) have an injury severity rating equal to or lower than MAIS 3, which suggests that seat belts in conjunction with airbags reduce occupant injury potential. Although this is the expected trend, more data, especially those with higher resultant occupant injury severity, is needed to ensure that the trend is not simply a nuance of this relatively small data set. There are a total of fourteen (14) unbelted occupants that have a span of longitudinal occupant impact velocities almost as large as the entire data set. Also, the unbelted occupants comprise a majority of the more severe injuries ($\text{MAIS} \geq 3$) sustained. Despite the small number of unbelted occupants, the current maximum longitudinal occupant impact threshold value appears to be a reasonable approximation of the upper limit of less severe occupant injury for unbelted occupants in this data set. Considering the deployment of the airbag in these cases, the maximum threshold value may have been set too high for the evaluation of unrestrained occupant injury in vehicles not equipped with airbags.

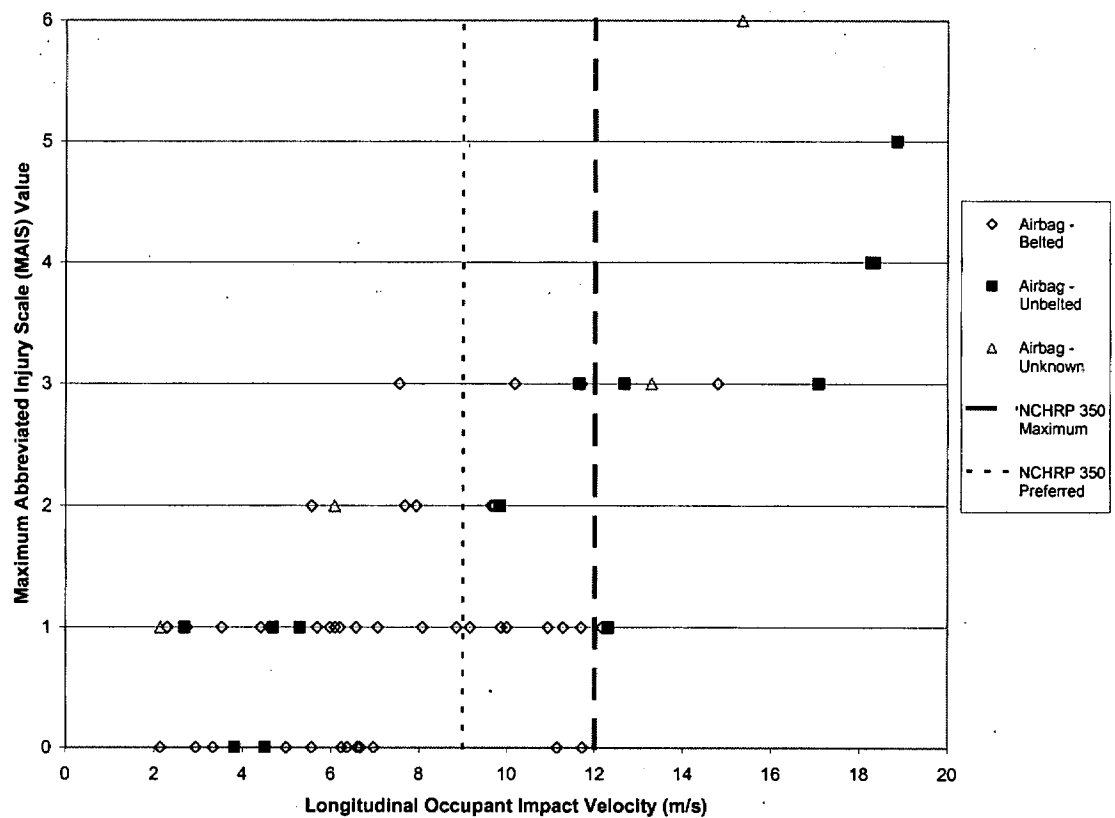


Figure 35. Occupant Impact Velocity: Maximum Occupant Injury In Single Event Frontal Collisions By NASS Belt Status

4.1.2 Occupant Injury By Body Region

The flail space model assumes that the occupant can be grossly represented by a point mass. Of all body regions, the chest and abdomen are best represented by a point mass. The arms, legs, and to a lesser extent, the head, are free to rotate about the occupant's center of gravity and are expected to be less well represented by the point mass assumption. To investigate this hypothesis, occupant injury for each body region is plotted as a function of occupant impact velocity. As the flail space model was only developed to predict overall occupant injury risk, however, this comparison is for exploratory purposes only.

Note that all plots in this section include data only from the single event, frontal deployment data set and are arranged by belt status. The data set for the body region analysis includes 51 belted occupants, 14 unbelted occupants and a single occupant with unknown belt status. Due to the presence of cases with a coded MAIS value but no associated body region injury information, there are slightly fewer cases (66 total instead of 69) than available for the investigation of maximum occupant injury. For cases with missing body region injury information and no sustained injury (MAIS = 0), all body region injury values have been assumed to be zero (0).

Occupant Head Injury

A significant relation between head injury and the occupant impact velocity is expected since the current NCHRP 350 longitudinal occupant impact velocity threshold limits were based on head impact experiments into windshields [9,10]. In addition, Ray et al. [28] found that an unrestrained ATD impacting the vehicle interior at 40 fps (12 m/s) approximately correlates to a Head Injury Criterion (HIC) value of 1000, the upper limit specified by FMVSS 208 for occupant protection in frontal collisions. Confounding factors, most notably the deployment of the airbag and the usage of active restraints, however, may mask the evidence of this correlation in this data set. To investigate head injury in relation to the flail space model, Figure 36 presents occupant head injury as a function of longitudinal occupant impact velocity. For comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines.

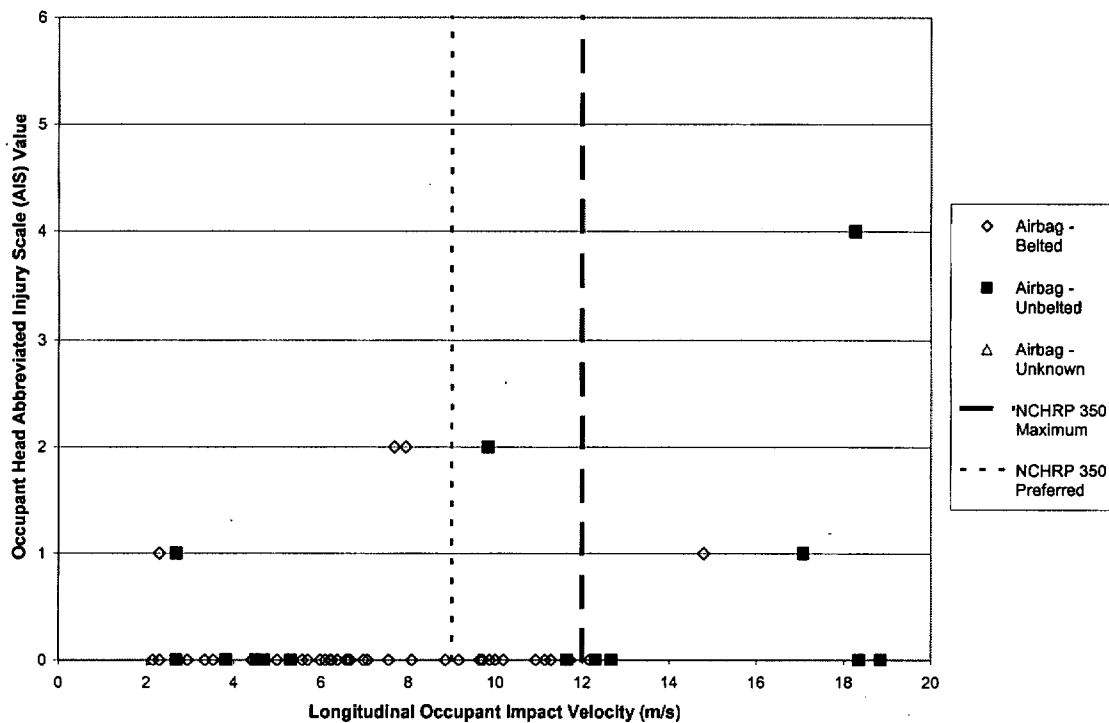


Figure 36. Occupant Impact Velocity: Occupant Head Injury In Single Event Frontal Collisions By NASS Belt Status

Examining Figure 36, however, occupant impact velocity appears to be a weak predictor of occupant head injury. There is a large horizontal scatter at the lower injury levels; AIS 1 values span from about 2 m/s up to 17 m/s while the AIS 0 values span from 2 m/s to 19 m/s. With respect to the current threshold, an occupant impact velocity in excess of this value does not result in severe injury in most cases (there is only one AIS 4 for occupant impact velocities in excess of the threshold). Also, there is substantial overlap and encapsulation of injury levels. For example, AIS 2 values are observed between 7 and 10 m/s while both AIS 0 and AIS 1 values are also observed in this range. This behavior could be a result of the size of the sample or the lack of cases with higher occupant impact velocity values. On the contrary, these results could be

attributed to the fact that the head is free to rotate with respect to the “point mass” portion of the body via the neck.

Figure 36 also appears to suggest that occupant head injury in this data set is not exceedingly sensitive to occupant seat belt usage. Out of six (6) unbelted cases where the longitudinal occupant impact velocity is in excess of the maximum threshold, only one has a significant head injury (AIS 4). Other than differences in occupant injury tolerances, this could be attributed to the deployment of the airbags in each of the analyzed cases. The airbag provides additional protection for the occupant’s head during a frontal collision, theoretically reducing the potential for serious head injury. In the case of the unbelted occupant, the injury-reducing potential of the airbag may mask any correlation between occupant impact velocity and resulting head injury.

Occupant Chest Injury

Although none of the longitudinal occupant impact velocity thresholds are based directly on human chest injury tolerance, this portion of the human anatomy is closest to the point mass representation assumed by the flail space model. As such, a strong correlation is expected between chest injury and the longitudinal occupant impact velocity. Figure 37 presents occupant chest injury as a function of longitudinal occupant impact velocity. For comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines.

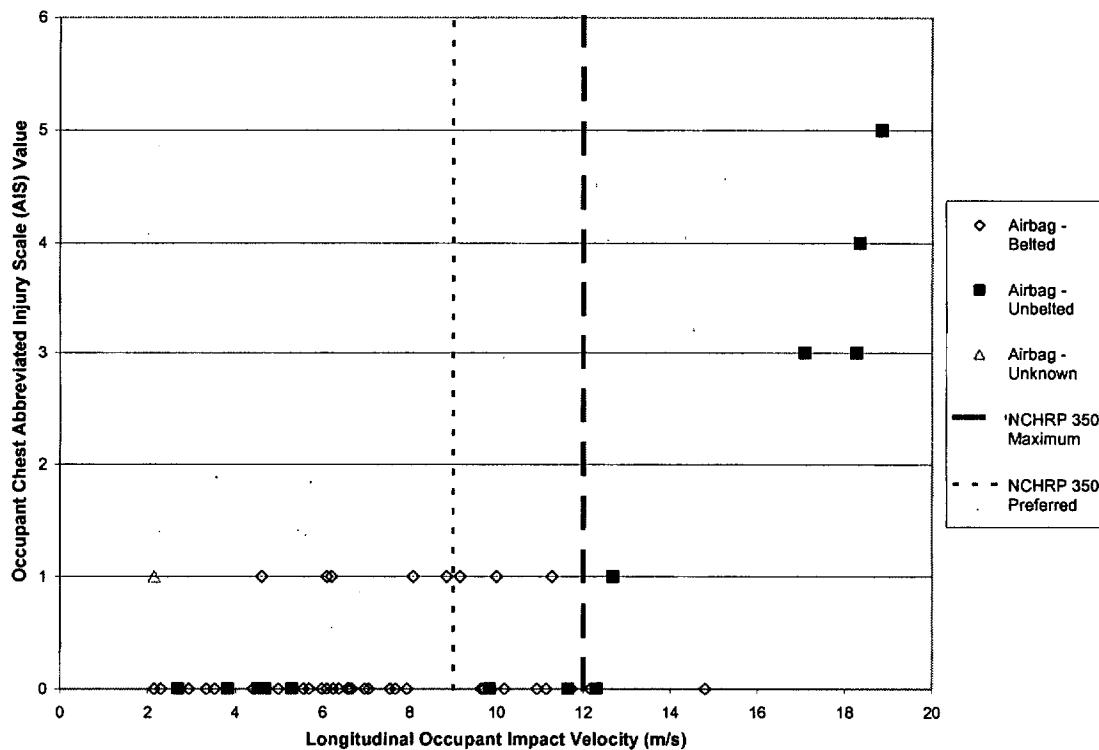


Figure 37. Occupant Impact Velocity: Occupant Chest Injury In Single Event Frontal Collisions By NASS Belt Status

Unlike occupant head injury, occupant impact velocity appears to be a good predictor of occupant chest injury in single event frontal collisions. The data follows the anticipated “diagonal band” trend with injury severity increasing as occupant impact velocity increases and there is a distinct break between the lower and higher severity injuries. All of the cases to the left of the NCHRP 350 maximum threshold are of lower severity ($AIS < 3$) while a majority of the cases that exceed the threshold are of higher severity ($AIS \geq 3$). With respect to Figure 37, the current maximum threshold of 12 m/s appears slightly conservative as an upper limit to less severe injury, but definitely within a reasonable range.

For unbelted occupants subjected to an occupant impact velocity below the maximum NCHRP 350 threshold, Figure 37 suggests that chest injury is not probable, as

all these occupants experienced no chest injury (AIS 0). For the belted occupants subjected to below-threshold occupant impact velocities, however, there appears to be a higher propensity for chest injury. Approximately fifteen (15) percent of the belted occupants (8 of 51) sustained chest injury (AIS 1). Although occupant injury tolerance differences are definitely a confounding factor, the higher potential for occupant chest injury at below-threshold occupant impact velocities may be at least partially a result of belt usage. Figure 37 also suggests that severe chest injury is likely for unbelted occupants experiencing an occupant impact velocity in excess of the NCHRP 350 threshold (4 of 6 occupants have $\text{AIS} \geq 3$). A lower potential for injury is expected for belted occupants experiencing an occupant impact velocity in excess of the threshold. Of the two (2) belted occupants subjected to an occupant impact velocity above the threshold, neither resulted in any chest injury (AIS 0). Although this is expected, more belted occupants subjected to excessive longitudinal occupant impact velocities are needed to test the hypothesis.

Occupant Upper Trunk Injury

The upper trunk, or area between the pelvis and neck (excluding the arms), of the human anatomy is most representative of the point mass suggested by the flail space model. Thus, the occupant impact velocity is expected to be a significant indicator of this type of injury. For the purpose of this study, the occupant upper trunk injury is defined as the maximum of the occupant chest, abdominal and spinal AIS values. Figure 38 presents occupant upper trunk injury as a function of occupant longitudinal occupant impact velocity. For comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines.

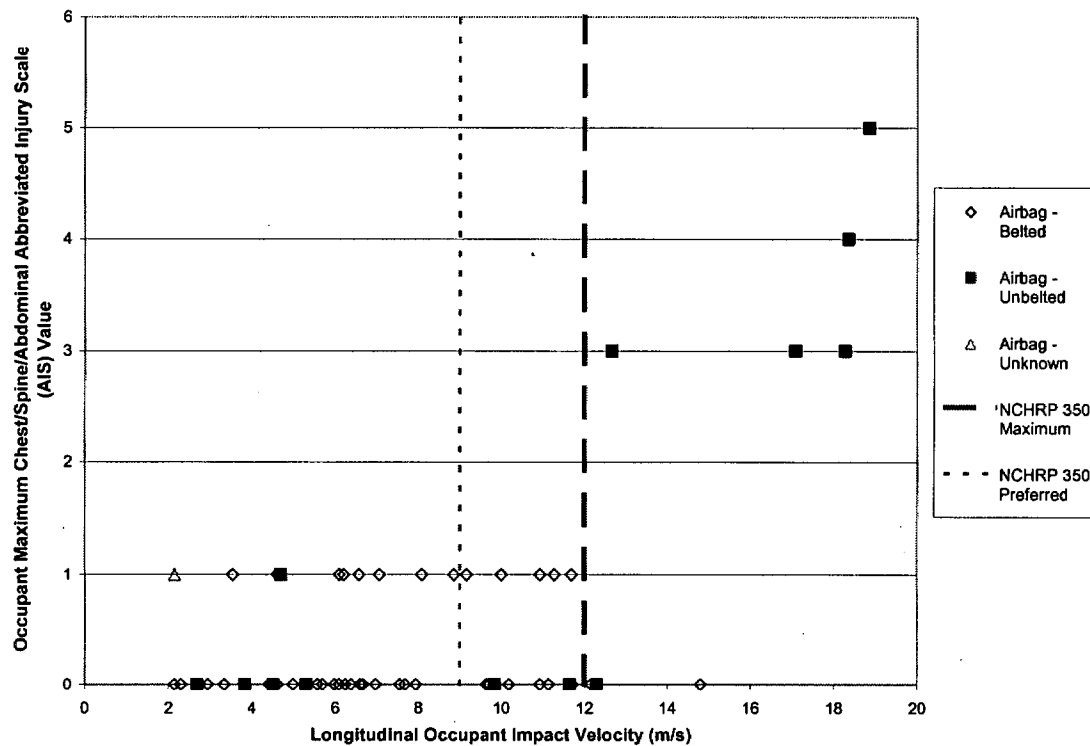


Figure 38. Occupant Impact Velocity: Occupant Upper Trunk Injury In Single Event Frontal Collisions By NASS Belt Status

As expected, Figure 38 suggests that occupant impact velocity is a substantial predictor of occupant upper trunk injury. The data follows the anticipated “diagonal band” trend with injury severity increasing as occupant impact velocity increases. Also, all of the cases to the left of the NCHRP 350 maximum threshold are of lower severity ($AIS < 3$) while a majority of the cases that exceed the threshold are of higher severity ($AIS \geq 3$). This implies that the current NCHRP 350 maximum longitudinal occupant impact velocity threshold value is a valid upper bound for less severe occupant upper trunk injury.

The plot is strikingly similar to Figure 37, occupant chest injury as a function of longitudinal occupant impact velocity. A comparison of the two plots reveals the following instances of increased injury severity: several belted occupants below the

NCHRP 350 maximum threshold (increased from AIS 0 to AIS 1), a single unbelted case above the threshold (increased from AIS 1 to AIS 3), and a single unbelted case below the threshold (increased from AIS 0 to AIS 1). The increase in injury potential among the belted occupants is most likely due to abdominal injury from the lap belt portion of the restraint. For the unbelted case above the current threshold, the increased injury suggests that the efficacy of the occupant impact velocity may increase with the inclusion of abdominal and spine injury.

Occupant Neck Injury

Since the neck is not well represented by the lump mass assumption, a strong correlation between the occupant impact velocity and occupant neck injury is not expected. Figure 39 illustrates occupant neck injury as a function of longitudinal occupant impact velocity. For comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines. Examining this plot, there is a significant amount of scatter among the data and no injury severity values above AIS 1. Both the AIS 0 and AIS 1 injury levels span approximately the same occupant impact velocity values (2 m/s to 18 m/s). The lack of the intuitive “diagonal band” trend and significant scatter and overlap of injury levels suggest that there is little or no correlation between the occupant impact velocity and occupant neck injury. Perhaps this type of injury is more prevalent in other types of collisions such as rear end collisions involving whiplash or simply that neck injury is far too complex to be accurately predicted with the use of the simplified occupant impact velocity measure.

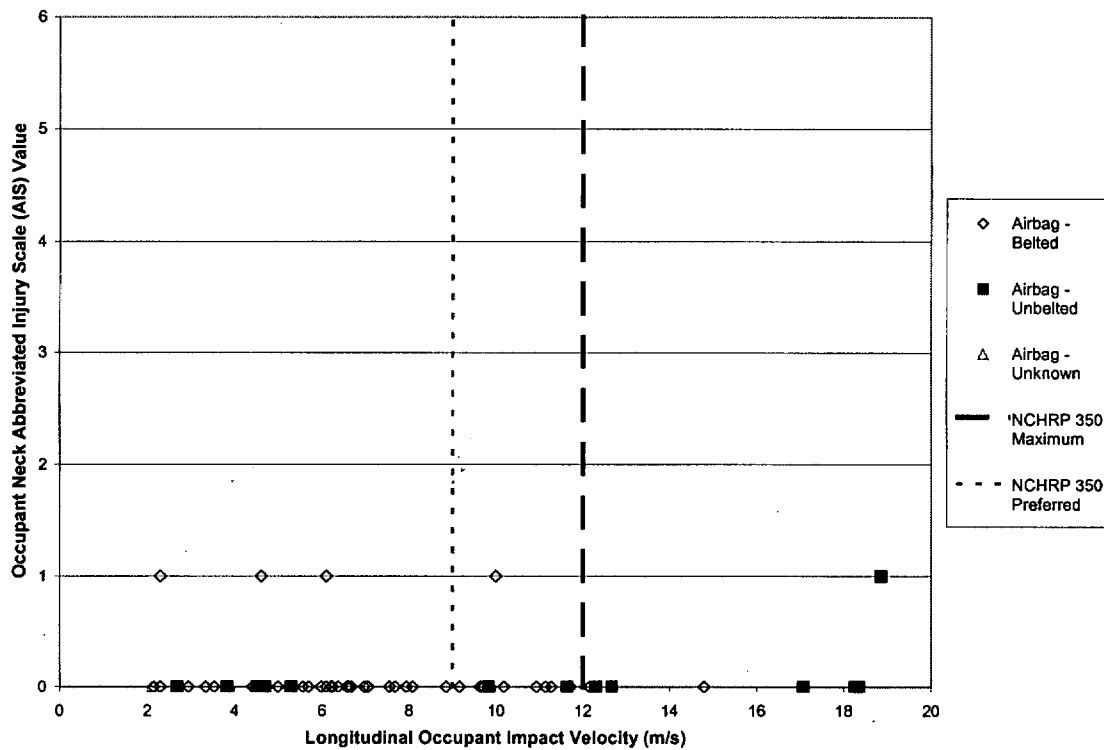


Figure 39. Occupant Impact Velocity: Occupant Neck Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Upper Extremity Injury

As they are free to rotate about the upper trunk, the arms may deviate significantly from the lump mass assumption of the flail space model. Thus, a significant correlation is not expected between occupant upper extremity injury and the occupant impact velocity. Figure 40 illustrates occupant upper extremity injury as a function of longitudinal occupant impact velocity and arranged by NASS seat belt status. Again, for comparison purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines. Note that the highest AIS value possible for an upper extremity injury is AIS 3.

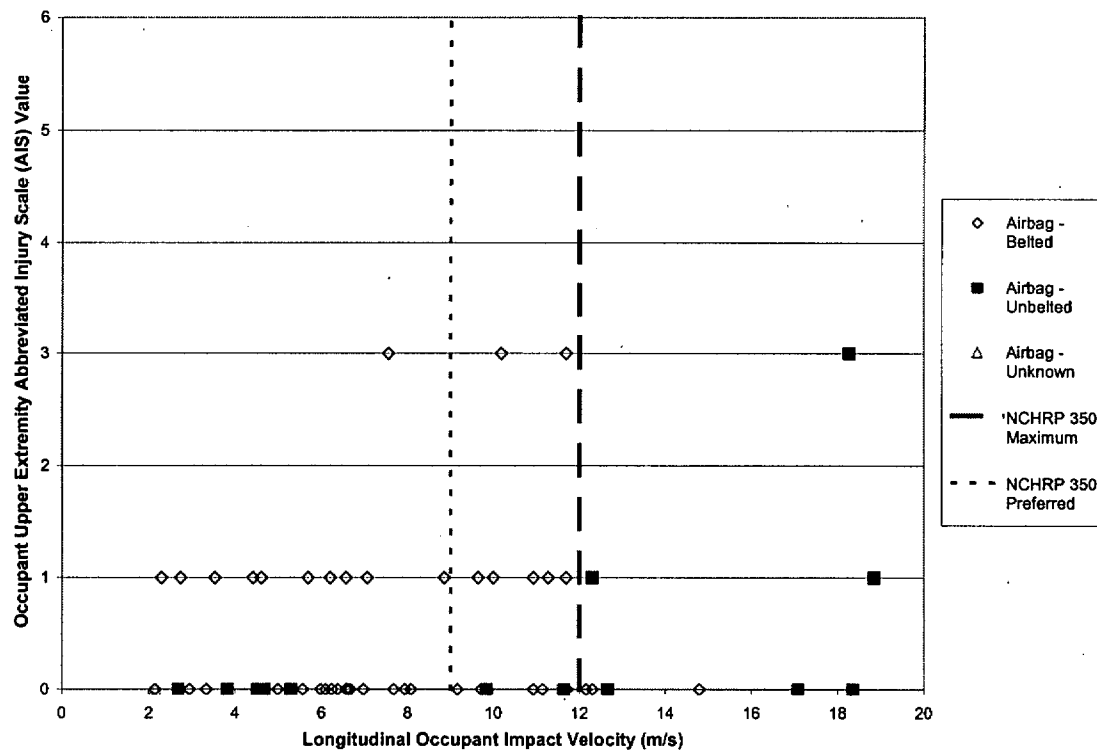


Figure 40. Occupant Impact Velocity: Occupant Upper Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Examining Figure 40, occupant impact velocity appears to be a weak indicator of occupant upper extremity injury for this set of single event frontal collisions. The data exhibits substantial scatter in the horizontal direction and overlap in the vertical direction (i.e. differing injury severity for the same occupant impact velocity values). With respect to the current NCHRP threshold, there is no indication that higher severity occurs at higher occupant impact velocity values as many points that exceed the threshold have little or no injury. Obviously, this data is subject to the same injury tolerance differences as the other body regions, which may impart the same influence on the scatter of the data. Of particular note, though, is the possible variation in occupant upper extremity position in the event of a collision. The actual position of the upper limbs may play a much more significant role in occupant injury than differences in injury tolerances.

Occupant upper extremity injury does not appear to be sensitive to occupant belt usage. Approximately twenty (20) percent of the unbelted occupants (3 of 14) exhibit upper extremity injury ($AIS > 0$) while approximately thirty-five (35) percent of restrained occupants (18 of 51) exhibit upper extremity injury. Although there is a slight disparity between these percentages, the scatter present in the plot further suggests that upper extremity injury is not sensitive to belt usage. For instance, all the unbelted occupants subjected to an occupant impact velocity below the current maximum threshold sustained no upper extremity injury. On the other hand, all the belted occupants that exhibit upper extremity injury are subjected to an occupant impact velocity lower than the threshold. As the belt is designed to keep the occupant from forcefully impacting the vehicle interior, a reduction in upper extremity injury is expected with occupant belt usage. The lack of this relation in the data supports the presence of confounding factors such as orientation of the upper limbs at the time of impact and the deployment of the airbag. Note that these conclusions, however, are not valid if the observations are simply an artifact of this rather small data set.

Occupant Lower Extremity Injury

Similar to the arms, the occupant lower extremities, or legs, are free to rotate about the upper trunk possibly creating a significant deviation from the lump mass assumption of the flail space model. As such, a strong correlation is not expected between occupant upper extremity injury and the occupant impact velocity. Figure 41 presents occupant lower extremity injury as a function of longitudinal occupant impact velocity. For comparison purposes, the NCHRP Report 350 maximum and preferable

longitudinal occupant impact velocity thresholds are plotted as dashed lines. Note the maximum injury severity threshold value for the lower extremity body region is AIS 5.

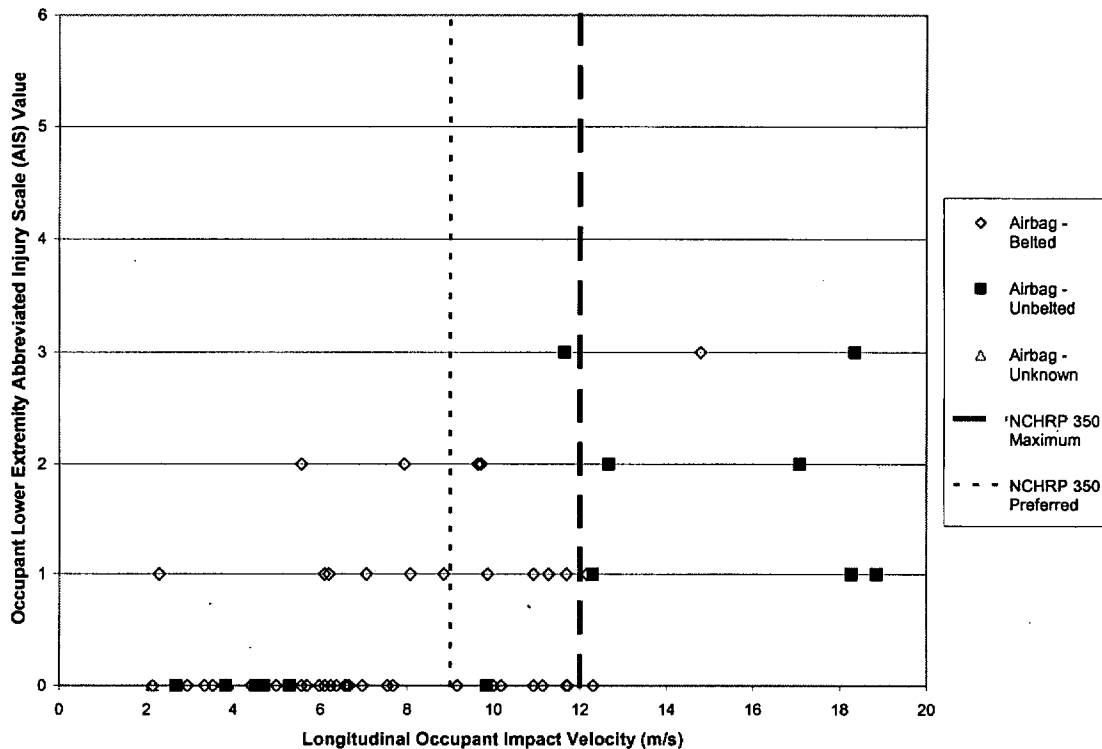


Figure 41. Occupant Impact Velocity: Occupant Lower Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Comparing Figure 40 and Figure 41, occupant impact velocity appears to be a better predictor of occupant lower extremity injury than upper extremity injury. Although the correlation is not as obvious as in upper trunk injury (see Figure 38), the correlation for lower extremity injury is substantially better than the correlation for upper severity injury. Other than the two AIS 1 cases at an occupant impact velocity values of approximately 19 m/s, the injury severity increases with increasing occupant impact velocity. One possible explanation could be that the lower extremities have fewer tendencies to vary position in comparison to the upper extremities resulting in behavior more representative of a point mass. With regard to the maximum NCHRP 350 occupant

impact velocity threshold, all the cases beneath the threshold exhibit less severe injuries ($\text{AIS} \leq 3$). Although injury severity generally increases with increasing occupant impact velocity, the cases exceeding the threshold did not sustain any lower extremity injury greater than AIS 3. One possible explanation of this could be the improvements to the interior padding of vehicles and vehicle designs that limit toe-pan intrusion during a collision.

The effect of occupant belt usage on lower extremity injury is difficult to discern qualitatively from Figure 41. For the unbelted occupants below the impact velocity threshold (with the exception of one case at 11.6 m/s), there is no evidence of lower extremity injury. On the other hand, the belted occupants subjected to occupant impact velocities below the threshold display lower extremity injury ($\text{AIS} > 0$) in approximately thirty (30) percent of the cases. Note that the pelvis is included in the lower extremity body region by the AIS scale, which may explain some of the injuries attained by the belted occupants. This same counter-intuitive phenomenon was observed in the upper extremity plot. From an overall perspective, however, belt usage appears to suppress lower extremity injury. Fifty (50) percent of the unbelted cases (7 of 14) resulted in lower extremity injury while approximately thirty (30) percent of the belted cases (16 of 51) resulted in lower extremity injury.

Occupant Spine Injury

Since the spine is a part of the upper trunk, a relatively strong relation between occupant impact velocity and injury to this body region is expected. The correlation, however, may be complicated by the rearward location of the spine in relation to the impacting surface. Figure 42 illustrates occupant spine injury as a function of

longitudinal occupant impact velocity with the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds plotted as dashed lines. Similar to the investigation of occupant neck injury, there is a considerable amount of scatter among the data and a deficiency of higher injury severity values. Of particular note is the AIS 0 injury level which spans occupant impact velocities from 2 m/s to approximately 20 m/s. The lack of the intuitive “diagonal band” trend coupled with the horizontal scatter suggests little or no relation between the occupant impact velocity and spine injury. As with neck injury, spinal injury may be more prevalent in other types of collisions (e.g. rear end collisions involving whiplash) or simply far too complex to be accurately predicted with the use of a single, simplified velocity-based measure.

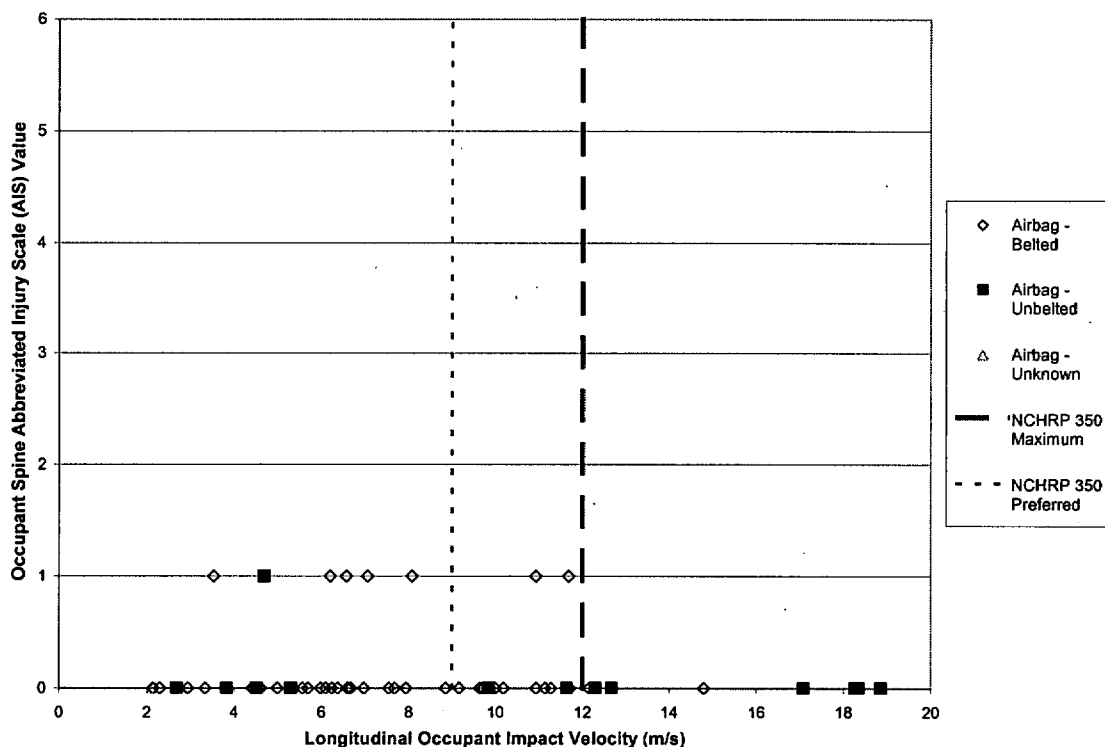


Figure 42. Occupant Impact Velocity: Occupant Spine Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Abdominal Injury

As the abdomen falls within the upper trunk body region of the human anatomy, a strong correlation between the occupant impact velocity and injury observed in this body region is expected. To investigate this hypothesis, Figure 43 is a plot of occupant abdomen injury as a function of occupant impact velocity with the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds plotted as dashed lines. The correlation of abdominal injury to occupant impact velocity appears more evident than the correlation for spine injury but weaker than the correlation to chest and upper trunk injury. Although there are some cases with a high impact velocity and no abdominal injury, there is some evidence of increasing injury with increasing impact velocity. All occupant impact velocities beneath the current maximum threshold exhibit injury levels equal to or less than AIS 1. For those cases exceeding the impact velocity threshold, there is evidence of more severe abdominal injury (two AIS 3 values) but a large proportion of cases (5 of 8) still exhibit no injury to this body region.

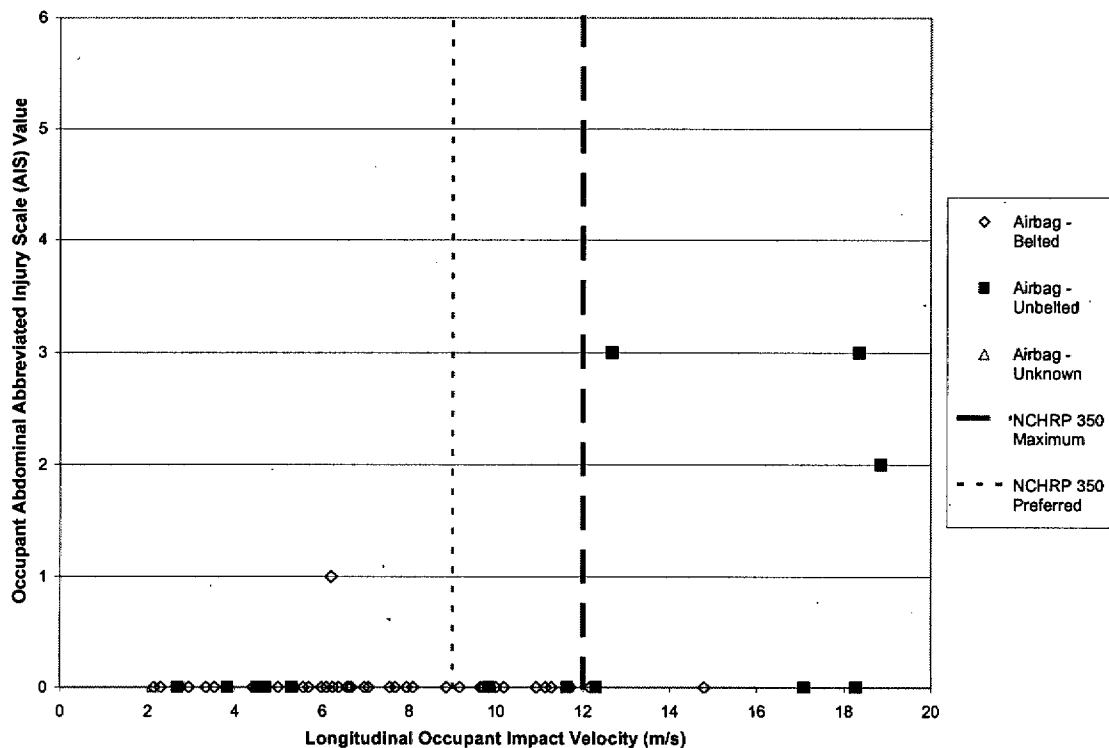


Figure 43. Occupant Impact Velocity: Occupant Abdominal Injury In Single Event Frontal Collisions By NASS Belt Status

With respect to the overall effect of occupant belt usage on abdominal injury, this data set reveals that restraints reduce the propensity for injury to this body region. Twenty-one (21) percent of the unbelted occupants (3 of 14) sustained abdominal injury while only a slim two (2) percent of belted occupants (1 of 51) sustained injury to this body region. Although observed in the lower and upper extremity injury plots, the possibility of abdominal injury does not appear dependent on belt usage for occupant impact velocities below the current NCHRP 350 maximum threshold. None of the unbelted occupants below the threshold exhibit any abdominal injury. For the belted cases below the threshold, only two (2) percent of the cases (1 of 50) display abdominal injury.

Occupant Face Injury

To investigate the correlation between facial injury and occupant impact velocity, Figure 44 presents the occupant face AIS value as a function of longitudinal occupant impact velocity in single event, frontal deployment cases. Again, the NCHRP Report 350 maximum and preferable longitudinal occupant impact velocity thresholds are plotted as dashed lines for comparison purposes. Because the face is part of the head and the threshold values are based principally on head impacts, a correlation between injury in this body region and the occupant impact velocity can be anticipated. Note, however, that strong correlation was not found between head injury and the occupant impact velocity in this data set. Examining Figure 44, a considerable amount of horizontal scatter is present among the data as well as an absence of injury severity values above AIS 1. Also, the injury levels present in the plot (AIS 0 and AIS 1) span approximately the same occupant impact velocities (2 m/s to 19 m/s). Both these observations imply that the occupant impact velocity is a weak predictor of facial injury. The deficiency of higher face injury severity values could be attributed to the fact that there are only a small number of facial injuries that can be severe and the highest attainable face injury severity value is an AIS 4. Nevertheless, if there were a strong relation between facial injury and occupant impact velocity, a significant number of the AIS 1 injuries would be present at higher occupant impact velocity values. For the effect of occupant restraints on injury, however, Figure 44 does suggest that facial injury is more prevalent among unbelted occupants. Half of the unbelted occupants experienced face injury while only twenty (20) percent of the belted occupants (10 of 51) sustained any facial injury.

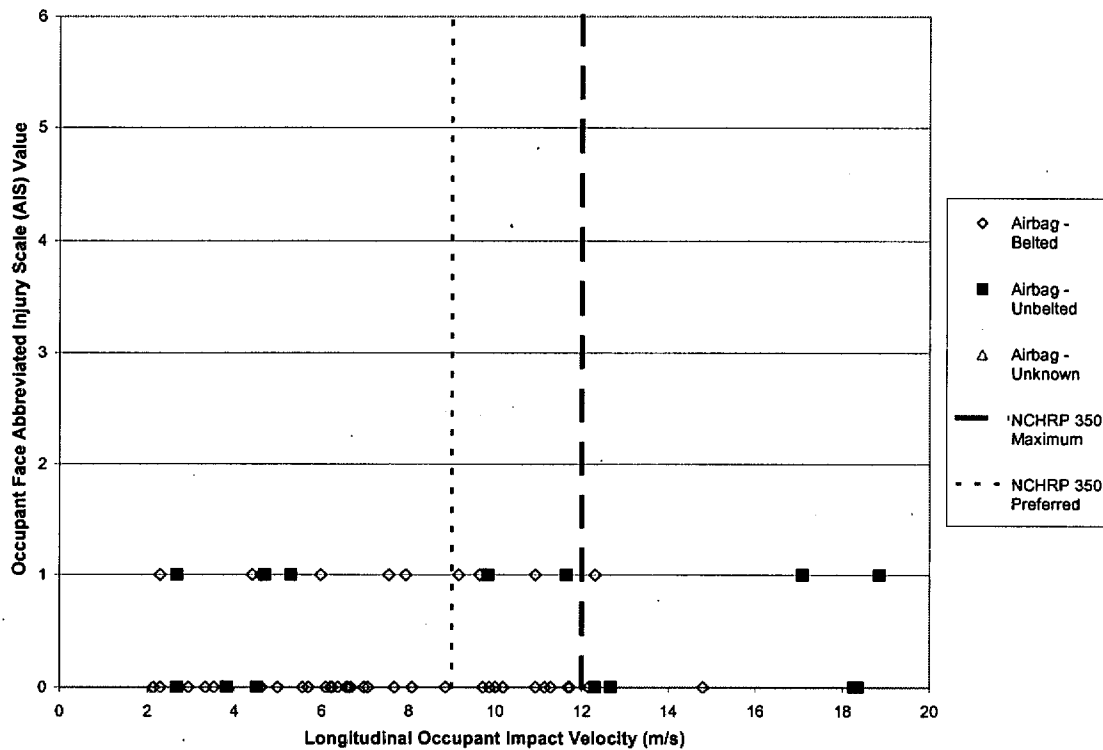


Figure 44. Occupant Impact Velocity: Occupant Face Injury In Single Event Frontal Collisions By NASS Belt Status

4.2 Occupant Ridedown Acceleration as a Predictor of Injury

4.2.1 Maximum Occupant Injury

Similar to the investigation of the efficacy of the occupant impact velocity, the maximum abbreviated injury scale (MAIS) values are plotted as a function of the longitudinal occupant ridedown acceleration to investigate the efficacy of occupant ridedown acceleration as a predictor of overall injury. Figure 45 is a plot for all the airbag deployment frontal collision cases in the database, which total 96 (77 left front seat occupants and 19 right front seat occupants). The data points are separated based on the position of the occupant within the front row of the occupant compartment (the flail space model estimates injury potential only for front seat occupants). For comparison

purposes, the NCHRP Report 350 maximum and preferable longitudinal occupant ridedown thresholds are plotted as dashed lines.

For the occupant impact velocity analysis, a total of 112 cases were available (91 left front seat occupants and 21 right front seat occupants). Note that the reduced data set available for the occupant ridedown portion of the analysis is a result of the exclusion of 16 cases where the EDR velocity was deemed “incomplete” but the occupant impact with the interior occurred prior to the termination of the EDR velocity data. In these cases, the occupant impact velocity is valid and has been included in the occupant impact velocity analysis. The computed ridedown acceleration in these cases, however, may not be valid since the captured velocity data is not “complete”. These cases have not been included in the occupant ridedown analysis.

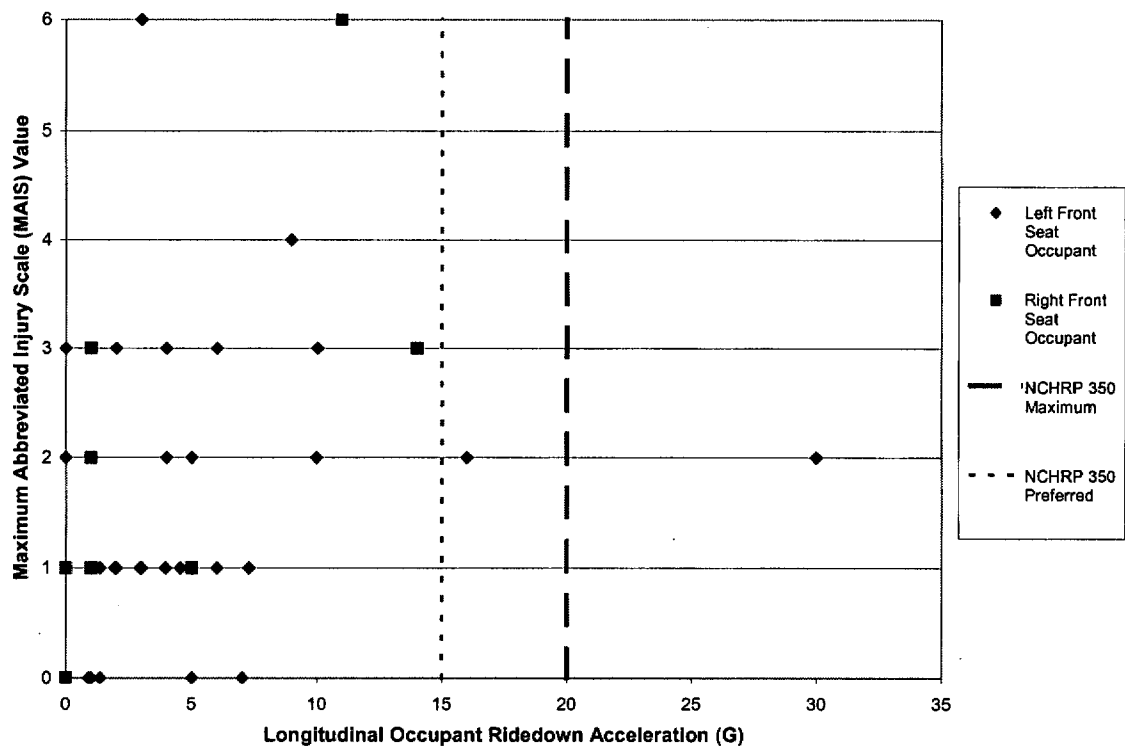


Figure 45. Occupant Ridedown Acceleration: Maximum Occupant Injury In Frontal Collisions

If the occupant ridedown acceleration is a valid indicator of occupant injury, injury severity will increase with increasing occupant ridedown accelerations. Also, if the current NCHRP 350 maximum longitudinal occupant ridedown acceleration threshold limit of 20 G is valid, a majority of the more serious injuries ($\text{MAIS} \geq 3$) should occur at occupant ridedown accelerations that exceed this limit. Figure 45 displays some of the anticipated “diagonal band” trend but all of the instances of severe injury occur at ridedown accelerations below the current thresholds. The only case where the occupant ridedown acceleration is in excess of the NCHRP 350 maximum limit has a low injury severity (MAIS 2). Also, there is significant overlap in the different injury severity levels. For instance, the MAIS 3 level spans from a ridedown of 0 G to approximately 15 G but all lower severity injuries (MAIS 0 through MAIS 2) also occur in this range. For this data set, the occupant ridedown acceleration appears to be a weak predictor of maximum occupant injury.

Since the frontal deployment data set used to generate Figure 45 includes multiple event collisions, there is a possibility that the GM EDR did not capture the injury-producing event of the collision. If this is the case, the comparison between the occupant ridedown acceleration and the injury will be erroneous. To investigate the affect of these multiple event collisions on the scatter of Figure 45, the data is plotted by the number of events per vehicle in Figure 46. The scatter of each different event classification is indicative of that found in the occupant impact velocity investigation; multiple event collisions appear both inside and out of the expected “diagonal band” trend.

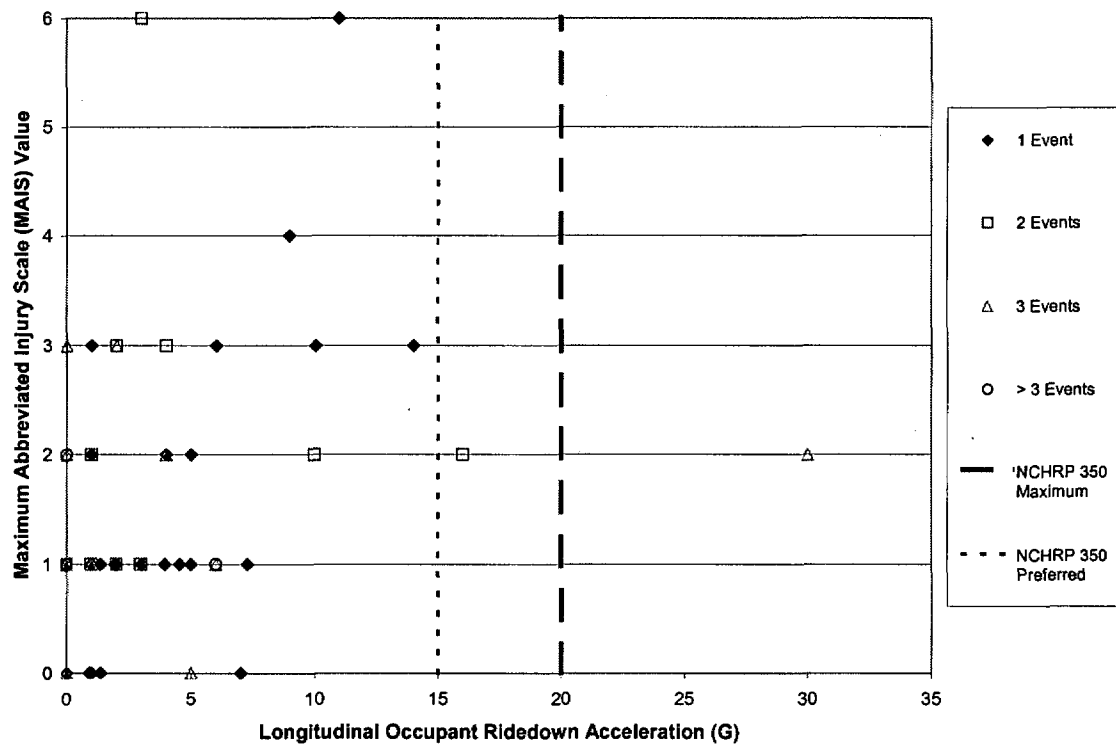


Figure 46. Occupant Ridedown Acceleration: Maximum Occupant Injury In Frontal Collisions By Number of Events

As in the occupant impact velocity investigation, the data set is narrowed to exclude multiple event collisions. This ensures that the GM EDR velocity information corresponds to the injury-producing event in the collision and that the analysis focuses on an area within the predictive scope of the flail space model. Figure 47 is a plot of maximum occupant injury as a function of occupant ridedown acceleration in single event, frontal deployment collisions and contains a total of 58 data points (44 left front seat occupants and 14 right front seat occupants). Again, the disparity between the available cases in the occupant impact velocity analysis is due to a number of cases where the EDR velocity information terminated immediately after the time of occupant impact with the vehicle interior.

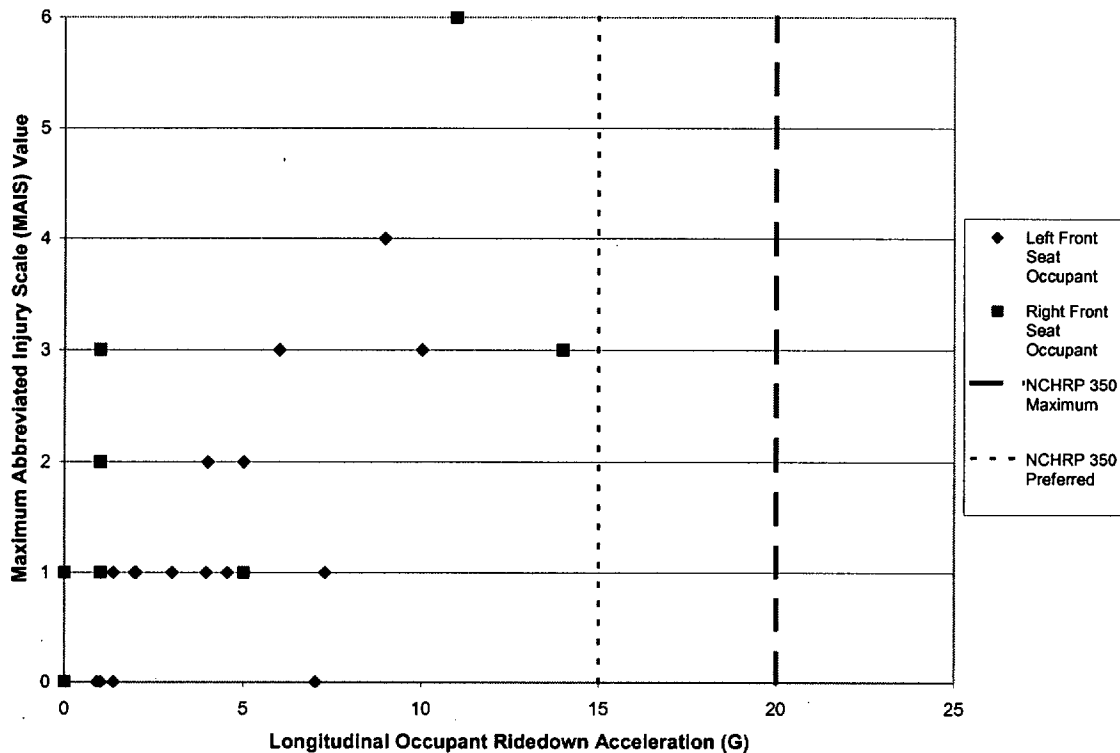


Figure 47. Occupant Ridedown Acceleration: Maximum Occupant Injury In Single Event Frontal Collisions

The restriction of the data set to single event collisions eliminated a number of the outliers but the remaining data still does not exhibit the level of correlation evident in the occupant impact velocity investigation, especially with respect to the threshold values. Despite the fact that the EDR-based value has been shown to provide a consistent over-estimate of the actual occupant ridedown acceleration, there are no cases above the maximum occupant ridedown acceleration threshold in this data set. Yet, for the data available, occupant injury ranges from no injury to fatal injury. One explanation is that this measure (with the current threshold values) is a relatively weak indicator of overall occupant injury, especially in comparison to the occupant impact velocity. Another possibility is that this data set simply does not have occupants injured because of excessive ridedown acceleration (i.e. the occupant impact velocity governs in each case).

Note that the referenced “diagonal band” in this case has a greater slope with respect to the threshold values than found in the occupant impact velocity investigation. This may be a result of the threshold values being set too high or simply an artifact of this small data set.

As the flail space model was designed to predict injury potential for an unrestrained occupant in a vehicle not equipped with an airbag, the model should provide the best estimate of injury for unbelted occupants. This prediction may be complicated, however, by the presence and deployment of airbags in the analyzed cases. To investigate how occupant belt usage affects overall occupant injury, Figure 48 presents maximum occupant injury in single event, frontal deployment collisions as a function of longitudinal occupant ridedown acceleration arranged by seat belt status. Identical to the occupant impact velocity investigation, the belt status has been obtained from the accident investigation data due to disparities between the GM EDR belt status and belt usage as reported by the accident investigators.

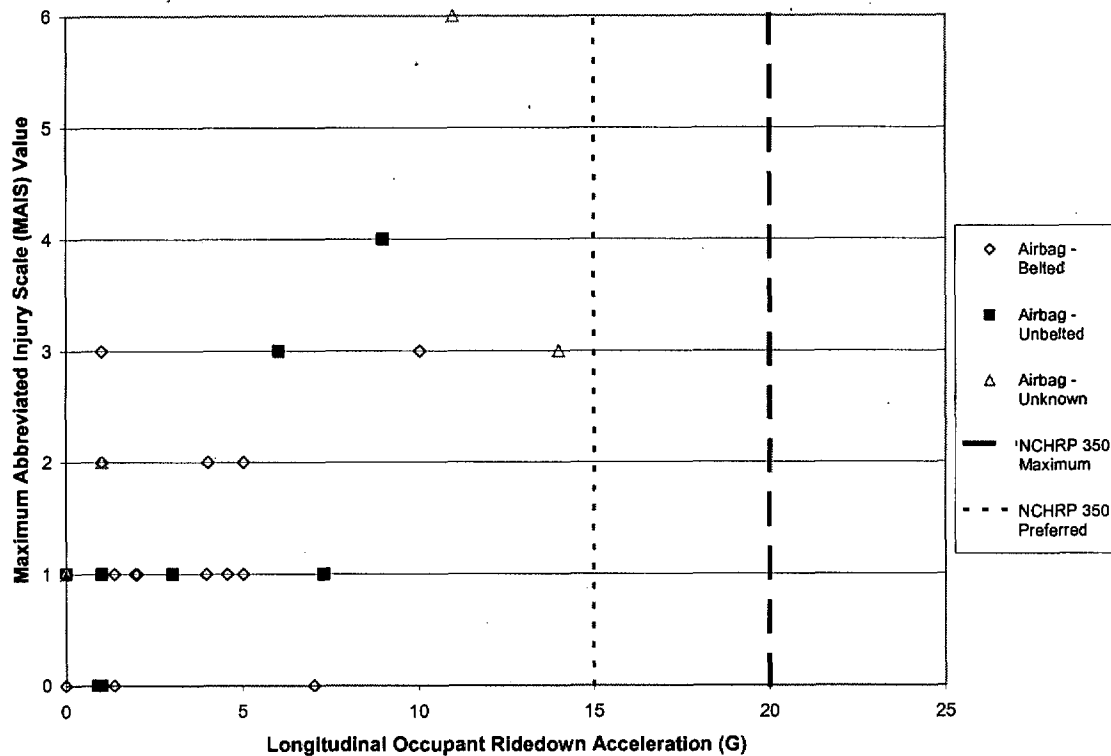


Figure 48. Occupant Ridedown Acceleration: Maximum Occupant Injury In Single Event Frontal Collisions By NASS Belt Status

Similar to the observed trend in the occupant impact velocity, the unbelted occupants are interspersed throughout Figure 48. If belt usage were a significant factor, a considerable amount of belted occupant data points would exist at high occupant ridedown accelerations in the less severe injury categories ($MAIS \leq 3$). There appears to be no evidence of belt usage reducing the severity of injury in terms of the occupant ridedown acceleration. This data set, however, is limited; more data may provide a better characterization of the influence of belt usage.

4.2.1 Occupant Injury By Body Region

As in the occupant impact velocity investigation, occupant injury is split by body region to investigate the injury predicting capabilities of the occupant ridedown

acceleration for different body regions. Note that all plots include data only from the single event, frontal deployment data set and are arranged by seat belt status. The data set for the occupant ridedown acceleration body region analysis includes forty-five (45) belted occupants, nine (9) unbelted occupants, and one (1) occupant with unknown seat belt status. Due to the presence of cases with a coded MAIS value but no associated body region injury information, there are slightly fewer cases (55 total instead of 58) than available for the investigation of maximum occupant injury. For cases with missing body region injury information and no sustained injury ($\text{MAIS} = 0$), all body region injury values have been assumed to be zero (0).

Unlike the threshold values for the occupant impact velocity, which are based principally on head impacts, the development of threshold values for the occupant ridedown acceleration is not particular to specific body regions. Instead the maximum and preferred limits appear to be blanket values derived using extensive reviews of human injury tolerance research [11,16]. Thus, the largest indicator of whether the occupant ridedown acceleration will be an effective predictor of occupant injury for a particular body region is how well that body region is represented by a lump mass.

Similar to the occupant impact velocity investigation, plots of injury severity as a function of the occupant ridedown acceleration are presented for each body region. Due to the lack of ridedown acceleration values in excess of the current thresholds in this data set, however, conclusions are not drawn for the effectiveness of this method at predicting injury to each body region. Nonetheless, it is interesting to note the “diagonal band” trend strongly evident only in the plot for occupant lower extremity injury.

Occupant Head Injury

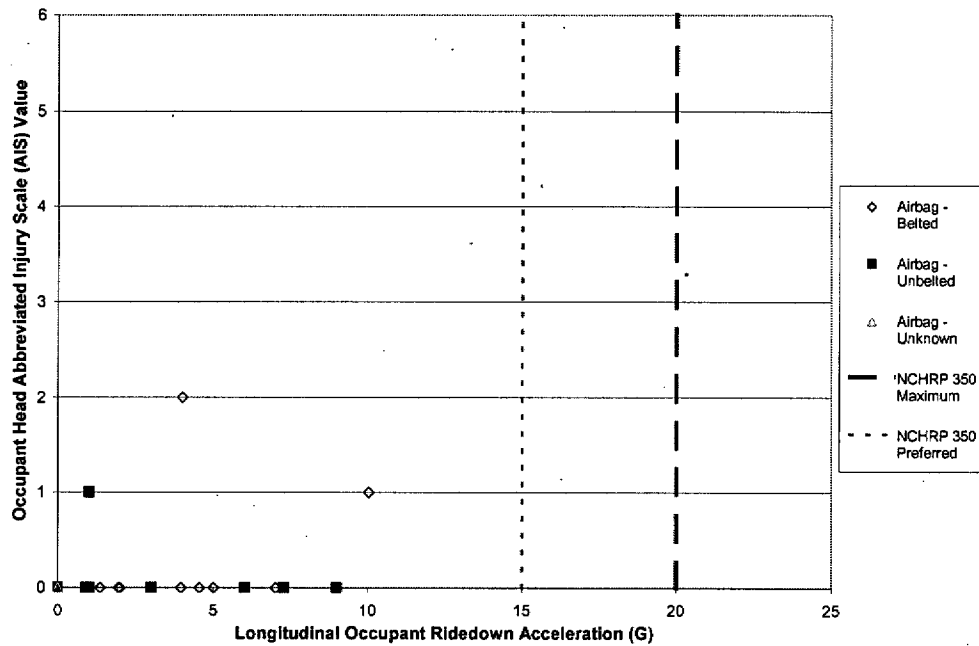


Figure 49. Occupant Ridedown Acceleration: Occupant Head Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Chest Injury

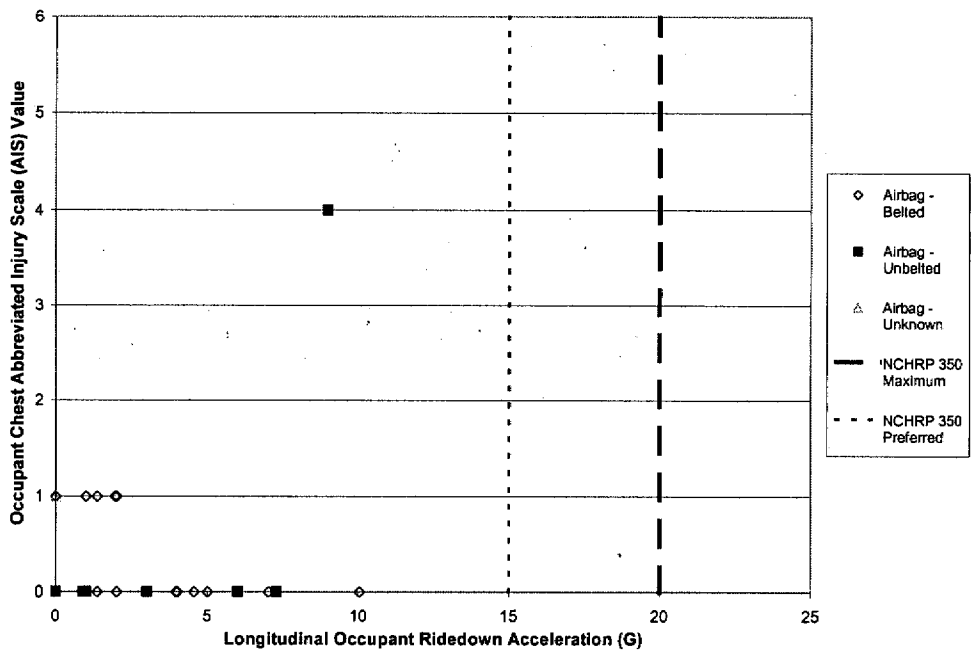


Figure 50. Occupant Ridedown Acceleration: Occupant Chest Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Upper Trunk Injury

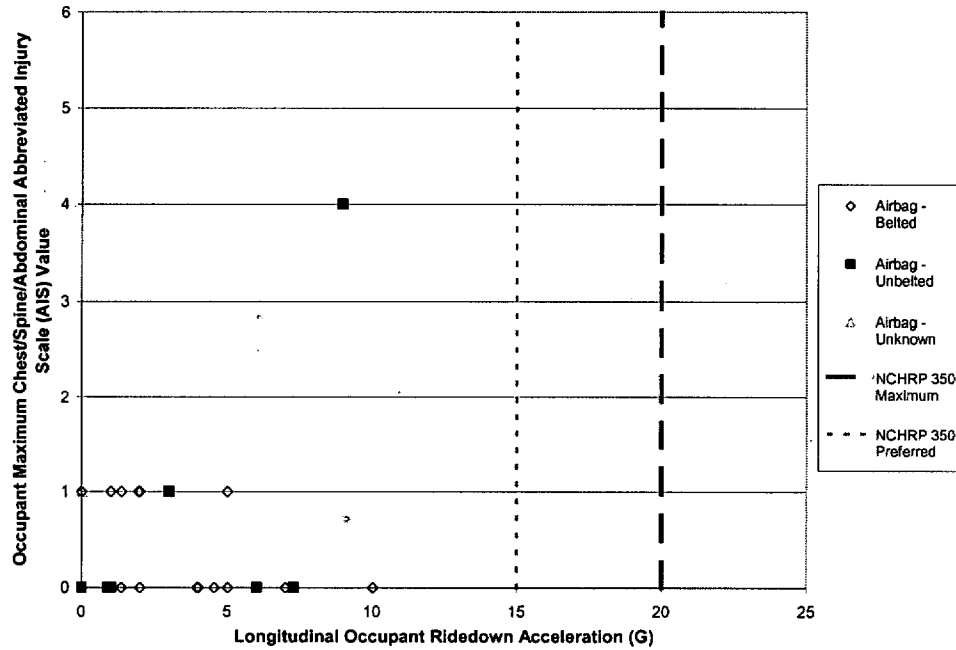


Figure 51. Occupant Ridedown Acceleration: Occupant Upper Trunk Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Neck Injury

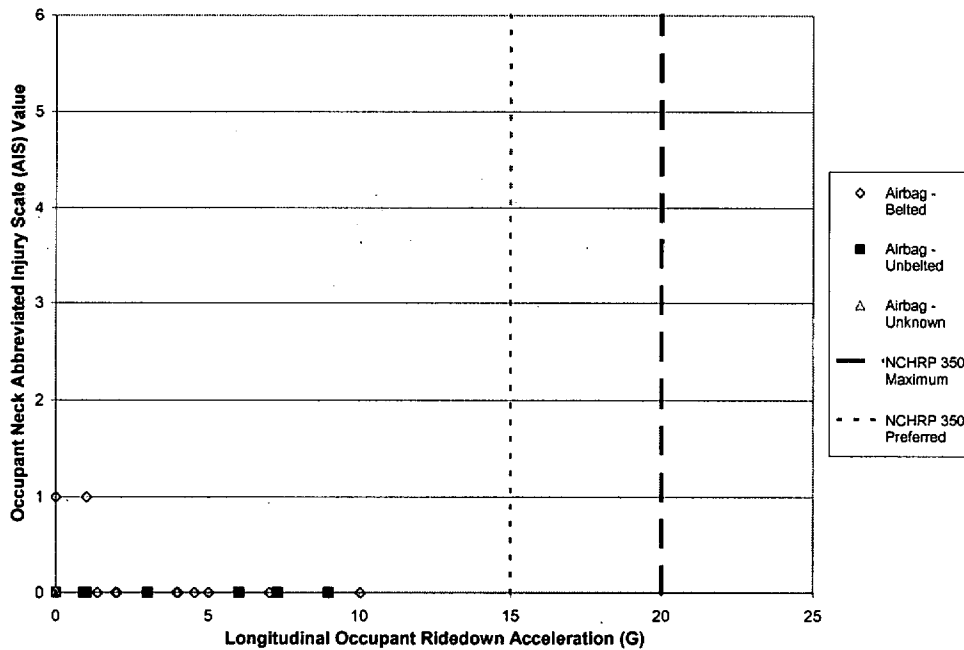


Figure 52. Occupant Ridedown Acceleration: Occupant Neck Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Upper Extremity Injury

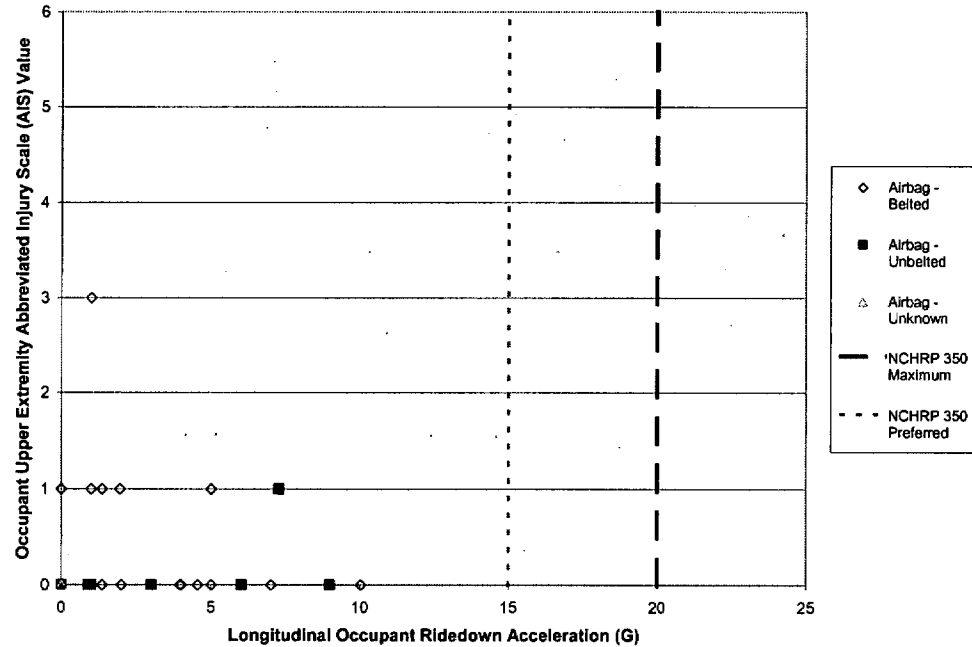


Figure 53. Occupant Ridedown Acceleration: Occupant Upper Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Lower Extremity Injury

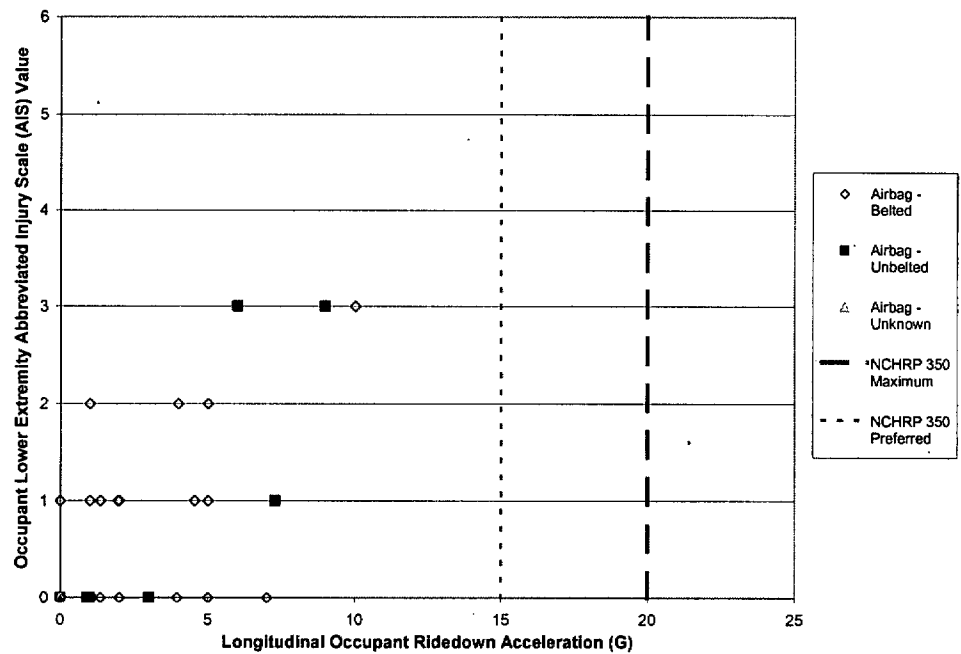


Figure 54. Occupant Ridedown Acceleration: Occupant Lower Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Spine Injury

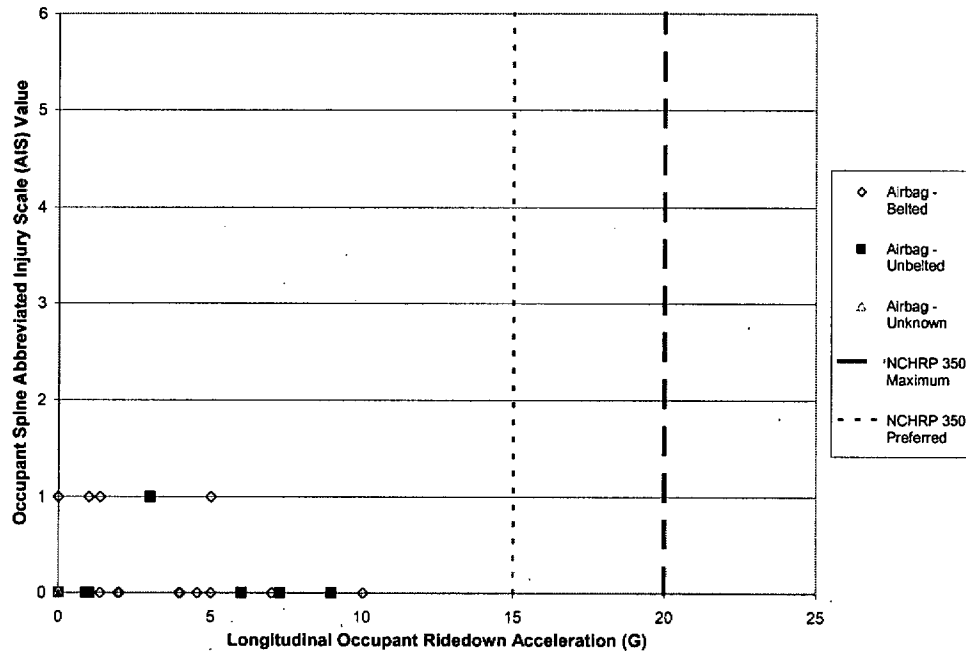


Figure 55. Occupant Ridedown Acceleration: Occupant Spine Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Abdominal Injury

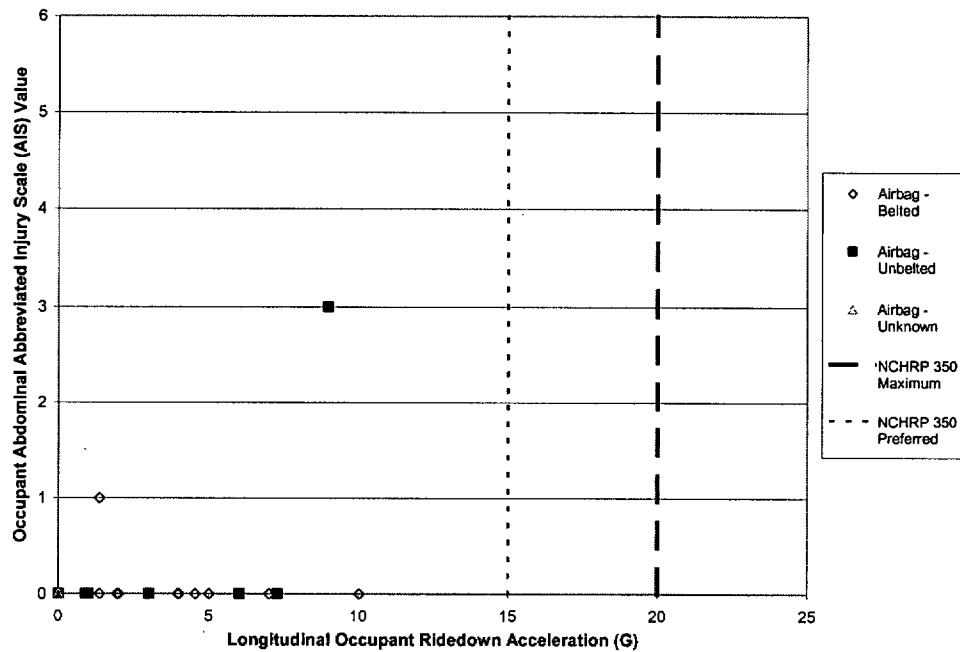


Figure 56. Occupant Ridedown Acceleration: Occupant Abdominal Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Face Injury

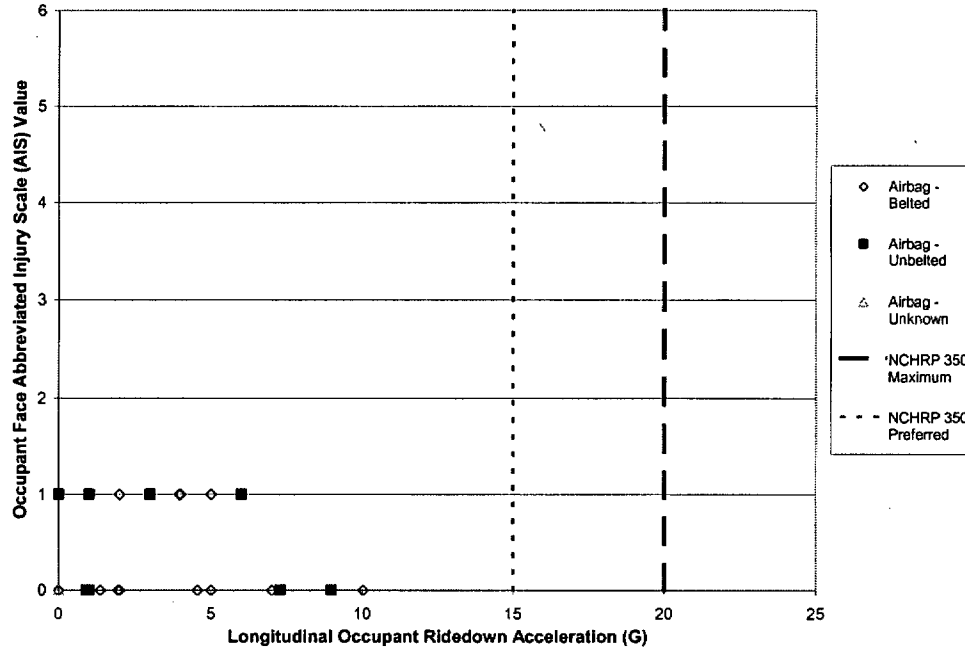


Figure 57. Occupant Ridedown Acceleration: Occupant Face Injury In Single Event Frontal Collisions By NASS Belt Status

4.3 Flail Space Model as a Predictor of Injury

Since the flail space model depends on both the occupant impact velocity and occupant ridedown acceleration for the evaluation of occupant injury potential, both need to be considered simultaneously to provide a comprehensive indication of the efficacy of the model. To facilitate this analysis, the plots from the individual analyses of the occupant impact velocity and occupant ridedown accelerations, in essence, are combined to illustrate occupant injury as a function of both these measures.

4.3.1 Maximum Occupant Injury

To investigate the overall predictive capabilities of the flail space model, the maximum abbreviated injury scale (MAIS) values are plotted as a function of both the longitudinal occupant impact velocity and subsequent longitudinal occupant ridedown

acceleration. Figure 58 is a plot for the ninety-six (96) suitable frontal deployment collisions in the database. The reduced number of cases, in comparison to the occupant impact velocity investigation, is a result of the inclusion of the occupant ridedown acceleration (i.e. only cases with an estimate of occupant impact velocity and occupant ridedown acceleration are included). Note that each series in the plot represents a different level of actual occupant injury based on the AIS scale. Lower severity injuries (MAIS < 3) are delineated with open points while higher severity injuries (MAIS ≥ 3) are delineated with closed points. For comparison purposes, the NCHRP Report 350 allowable thresholds for occupant impact velocity and occupant ridedown acceleration are plotted as dashed lines resulting in a threshold “box”.

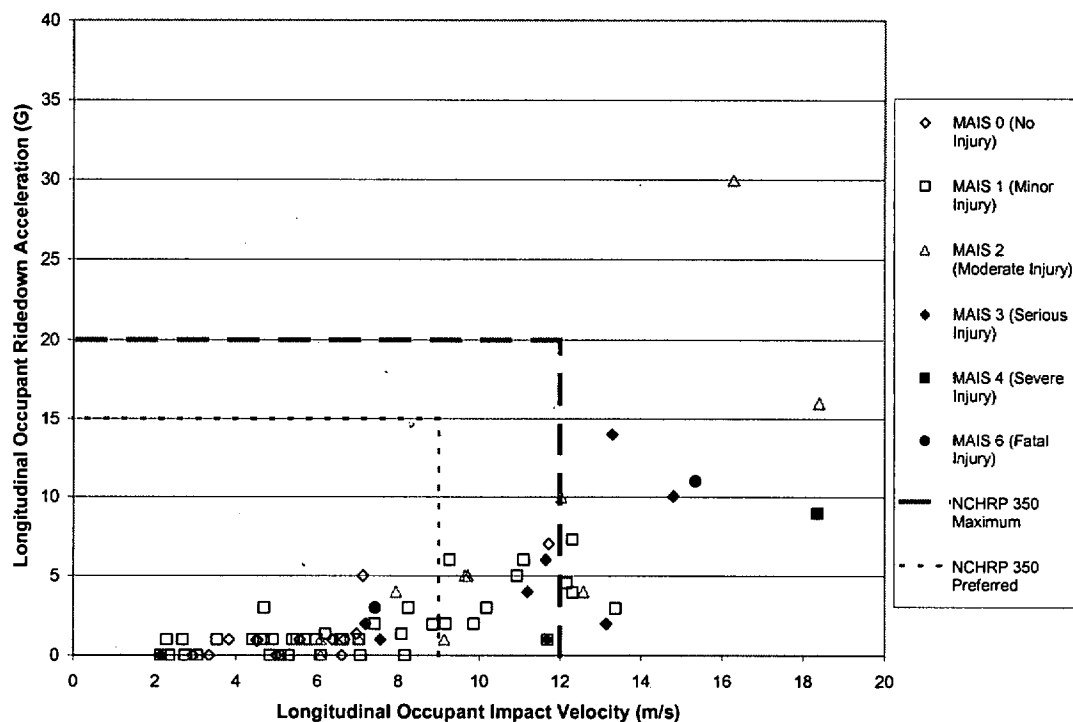


Figure 58. Maximum Occupant Injury In Frontal Collisions

Intuition dictates that the more severe injuries should occur at both higher occupant impact velocities and higher occupant ridedown accelerations. If the current

longitudinal NCHRP 350 limits are valid, a majority of the closed points should occur outside of the delineated threshold “box”. Figure 58 does not illustrate a strong correlation of occupant injury to the flail space model criteria. For the cases where either measure is in excess of the current NCHRP 350 longitudinal limits, only thirty-eight (38) percent of the occupants (5 of 13) sustained severe injury ($\text{MAIS} \geq 3$). Considering only the severe injury cases in the data set ($\text{MAIS} \geq 3$), only forty (40) percent of the cases (5 of 12) fall outside of at least one of the NCHRP 350 thresholds. Conversely, for the cases of lower severity injury ($\text{MAIS} < 3$), ninety (90) percent are within both NCHRP 350 maximum threshold values. Note that only approximately one (1) percent of the cases (1 of 96) are in excess of the longitudinal occupant ridedown acceleration limits set by NCHRP 350.

Since the frontal deployment data set used to generate Figure 58 includes multiple event collisions, there is a possibility that the GM EDR did not capture the injury-producing event of the collision. If this is the case, the comparison between the flail space model and the attained injury will be erroneous. These invalid comparison points may be a reasonable explanation for the occurrence of higher severity injury at occupant impact velocity and occupant ridedown accelerations beneath the NCHRP 350 thresholds in Figure 58. To ensure that the comparison between the injury attained and the flail space model, the data set is narrowed to include only single event, frontal deployment collisions. Figure 59 presents maximum occupant injury as a function of both occupant impact velocity and ridedown acceleration for this narrowed data set. Since the data set is again restricted to those cases that have an estimate of the occupant ridedown acceleration, there are a total of fifty-eight (58) cases available for analysis. Again, open

points indicate the lower severity injury (MAIS < 3) instances, closed points represent the more severe injury instances (MAIS ≥ 3), and the current NCHRP 350 thresholds are plotted as dashed lines.

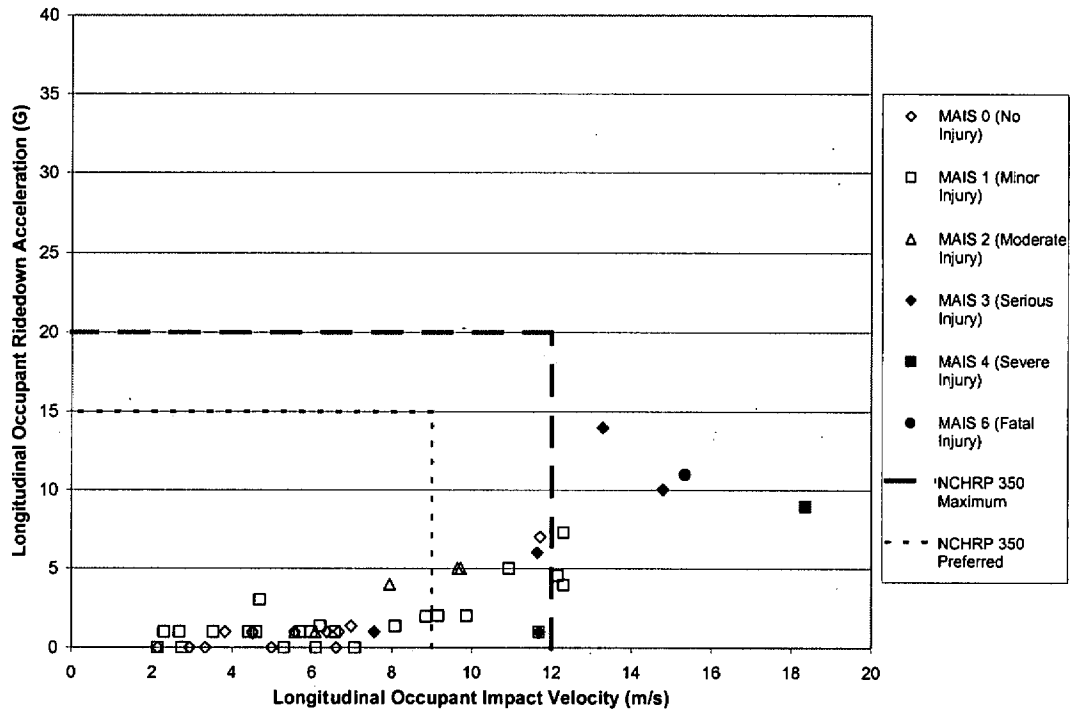


Figure 59. Maximum Occupant Injury In Single Event Frontal Collisions

From the available data, the flail space model appears to be a strong indicator of maximum occupant injury in single event, frontal deployment collisions. Figure 59 demonstrates the expected trend that appears more a result of the occupant impact velocity. As expected, a majority of the open points occur within the current NCHRP 350 threshold “box”. For the more serious MAIS 3 values, about sixty (60) percent of the values are within the “box”, while the remaining forty (40) percent fall outside the current limits. All the other closed points fall outside of the current threshold “box”. Also, of all the cases in excess of either threshold, approximately sixty (60) percent of the occupants sustained severe injury (MAIS ≥ 3). Note that even though the occupant

ridedown acceleration is overestimated, no cases in this restricted data set exceed even the “preferred” occupant ridedown acceleration threshold of 15 G prescribed by NCHRP 350. Again, this suggests that the occupant ridedown acceleration is not as significant in the prediction in overall injury in comparison to the occupant impact velocity.

4.3.2 Occupant Injury By Body Region

As in the occupant impact velocity and occupant ridedown acceleration investigations, occupant injury is split by body region to investigate whether the flail space model is a better indicator of occupant injury to certain body regions. Again, as the flail space model was only developed to predict overall occupant injury risk, these comparisons are for exploratory purposes only. Note that all plots include data only from the single event, frontal deployment data set and include forty-five (45) belted occupants, nine (9) unbelted occupants, and one (1) occupant with unknown seat belt status. Due to the presence of cases with a coded MAIS value but no associated body region injury information, there are slightly fewer cases (55 total instead of 58) than available for the maximum occupant injury analysis. Note, however, that missing body region information cases include two occupants with severe injury (one MAIS 6 and one MAIS 3). For the cases with missing body region injury information and no sustained injury (MAIS = 0), all body region injury values have been assumed to be zero (0).

Since the investigation of the combination of the occupant impact velocity and occupant ridedown acceleration is limited to cases that have an estimate for both measures, the data set available is subject to the same limitations of the occupant ridedown acceleration. As such, the lack of ridedown acceleration values in excess of the thresholds coupled with the lack of body region injury information for two of the severe

injury cases in this data set prevents conclusions regarding the effectiveness of the flail space model at predicting injury to each body region.

Occupant Head Injury

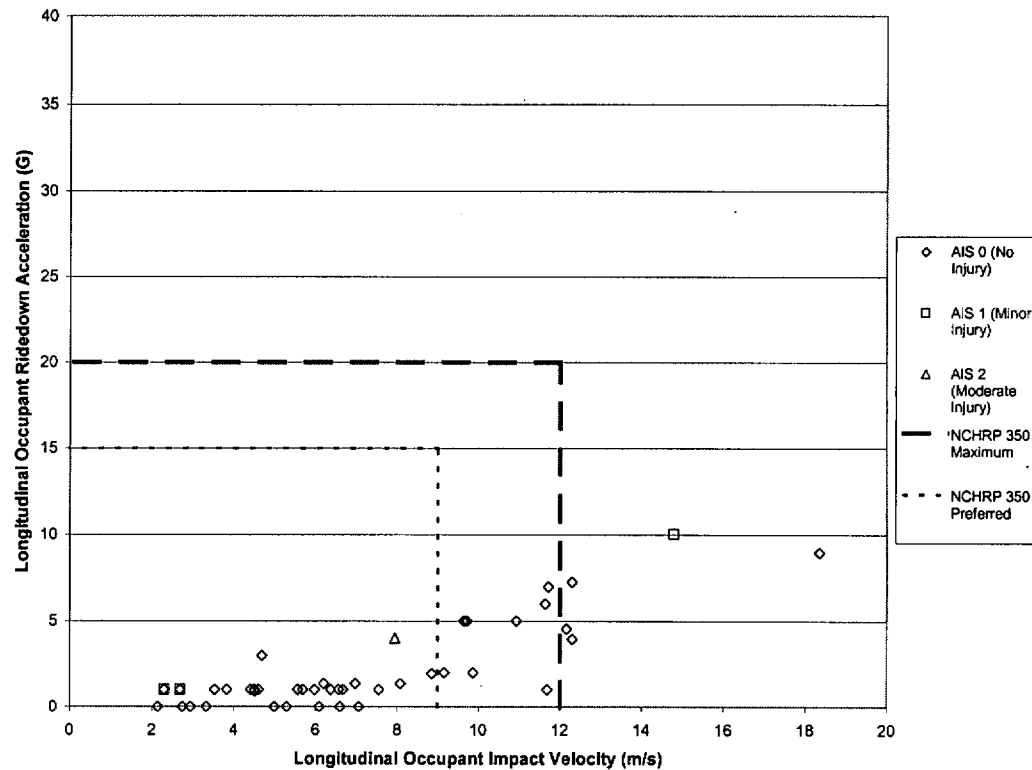


Figure 60. Flail Space Model: Occupant Head Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Neck Injury

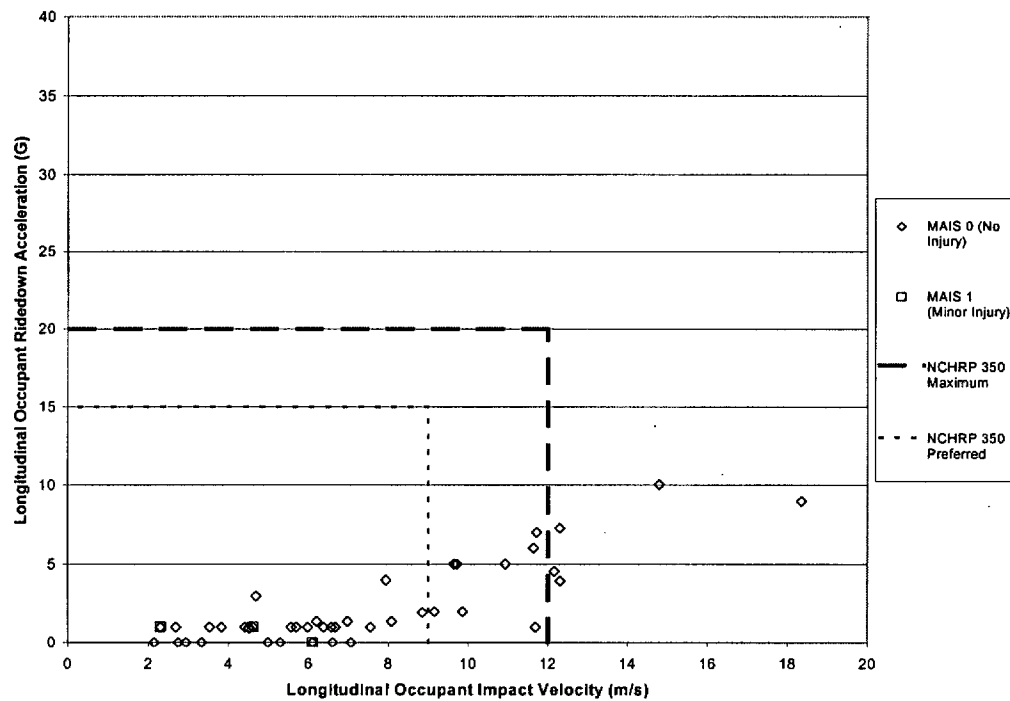


Figure 63. Flail Space Model: Occupant Neck Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Upper Extremity Injury

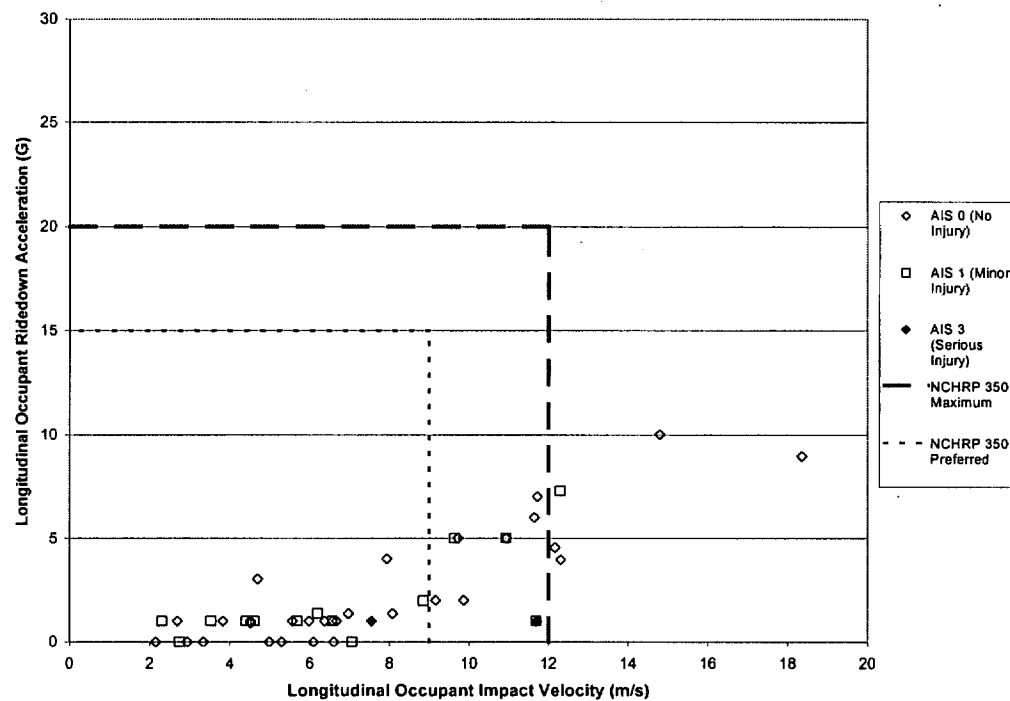


Figure 64. Flail Space Model: Occupant Upper Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Lower Extremity Injury

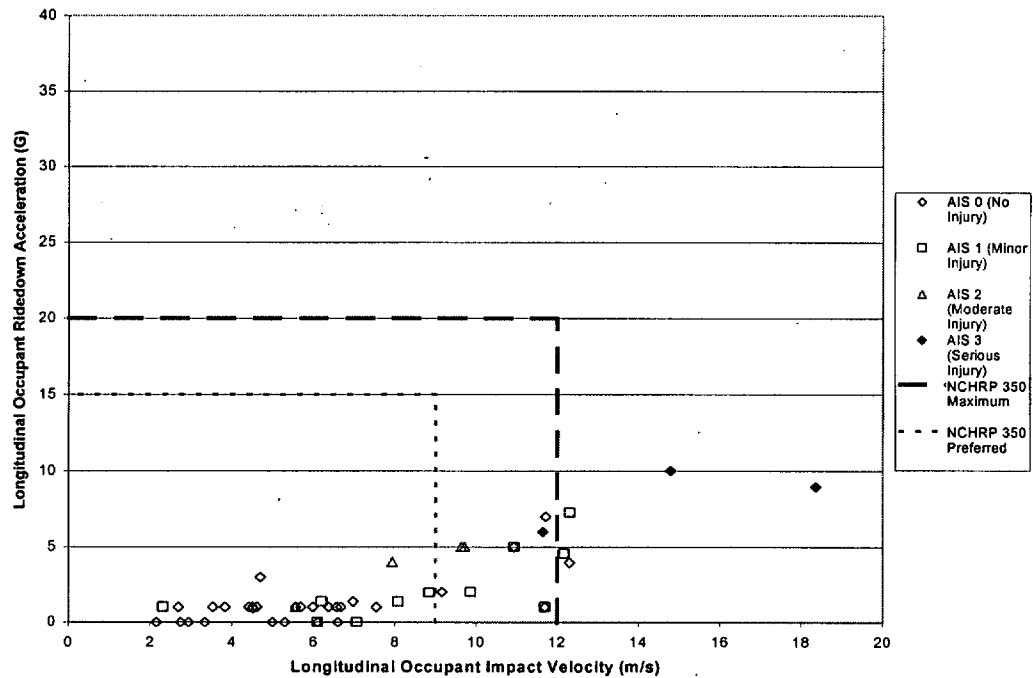


Figure 65. Flail Space Model: Occupant Lower Extremity Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Spine Injury

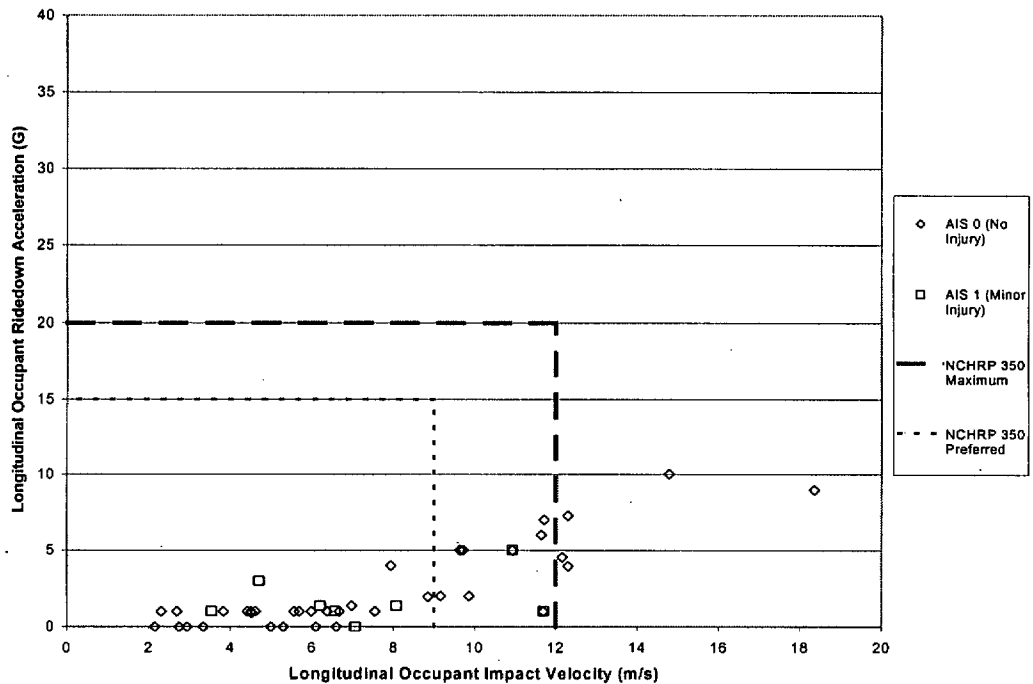


Figure 66. Flail Space Model: Occupant Spine Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Abdominal Injury

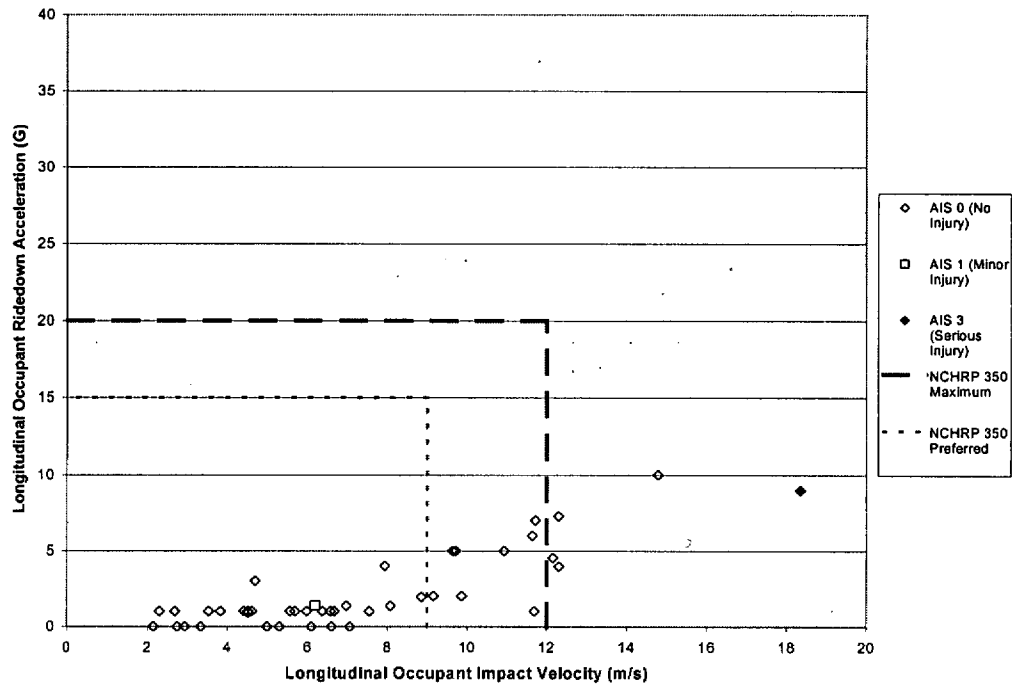


Figure 67. Flail Space Model: Occupant Abdominal Injury In Single Event Frontal Collisions By NASS Belt Status

Occupant Face Injury

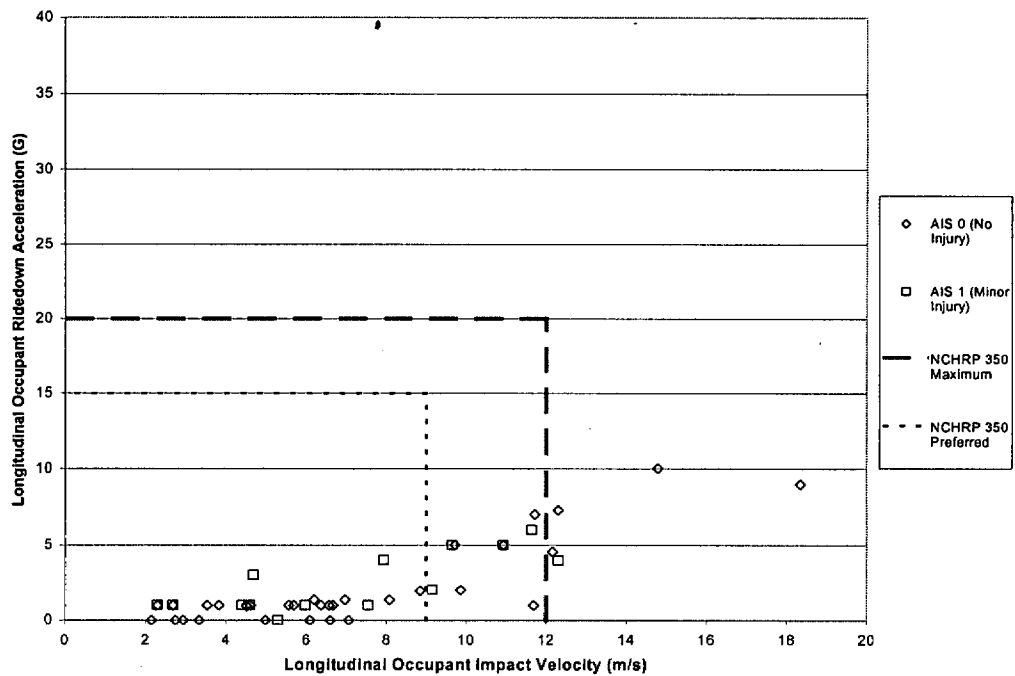


Figure 68. Flail Space Model: Occupant Face Injury In Single Event Frontal Collisions By NASS Belt Status

4.4 Summary of Results

Table 8 presents a summary of the level of correlation of the flail space model to overall injury and injury to different body regions for single event frontal deployment collisions within the Rowan EDR database. Note that these preliminary qualitative conclusions have been based on a small data set for exploratory purposes only. An increased data set with more instances of severe injury and occupant risk values in excess of the NCHRP 350 thresholds will permit the use of statistical techniques to determine level of correlation and may alter the following observations.

Table 8. Summary of Flail Space Model Efficacy

Injury Prediction Type	Flail Space Model Criteria Predictive Capability		
	Occupant Impact Velocity	Occupant Ridedown Acceleration	Combination
Maximum	Strong	Weak	Strong
Head	Weak	N/A	N/A
Chest	Strong	N/A	N/A
Upper Trunk	Strong	N/A	N/A
Neck	None	N/A	N/A
Upper Extremity	Weak	N/A	N/A
Lower Extremity	Moderate	N/A	N/A
Spine	None	N/A	N/A
Abdominal	Weak	N/A	N/A
Face	None	N/A	N/A

CHAPTER 5 – LIMITATIONS

As with any study of this nature, the results should be considered in parallel with the limitations inherent to the available data and methodology utilized. These include, but may not be limited to, the following items:

- Size of the available data set
- Distribution of the flail space criteria
- Absence of lateral information
- Occupant ridedown acceleration computation
- GM EDR recording duration
- Exclusion of other vehicle manufacturers
- Occupant compartment intrusion

A description of each enumerated study limitation and the surrounding issues are provided below.

5.1 *Size of the Available Data Set*

Table 9 provides a summary of the number of cases available for each portion of the analysis of the efficacy of the flail space model: the occupant impact velocity, the occupant ridedown acceleration, and the combination of these measures. Note that the numerical values correspond only to the available single event frontal collisions and that none of these values exceed one hundred (100) cases. With respect to the approximately 6 million police-reported automobile accidents per year [48], the data set for this analysis is relatively insignificant. The data element size, however, is comparable to order of

magnitude of the previous studies. Council and Stewart [27], in their attempt to define the relation between the pre-flail space occupant risk criteria and occupant injury, utilized a total of 232 cases (matches between crash tests and actual vehicular collisions). For the attempt to investigate the occupant impact velocity and occupant ridedown acceleration, the same study utilized only 62 cases. Ray et al. [28], in their evaluation of the lateral occupant impact velocity, utilized a total of only seventeen (17) cases. Although the magnitude of data is equivalent to the previous studies, additional data will provide further insight into the important correlation between occupant injury and the flail space model.

Table 9. Number of Cases Available for Analysis

Injury Category	Flail Space Model		
	OIV	ORA	Combination
Maximum Injury	69	58	58
Body Region Injury	66	55	55

Since the flail space model was designed to indicate injury potential for unbelted occupants, these cases of are particular interest. In addition, instances of high occupant injury severity are required to provide the basis for an analysis. The size of the current data set limits the availability of both of these case types. For the available data, there are only 14 and 9 unbelted cases for the occupant impact velocity and occupant ridedown acceleration analyses, respectively. Likewise, there are only 12 and 7 cases of severe maximum occupant injury ($\text{MAIS} \geq 3$) in the occupant impact velocity and occupant ridedown acceleration analyses, respectively. More of these case types are required to determine the effectiveness of the flail space model at predicting occupant injury potential.

5.2 Distribution of the Flail Space Criteria

Additional cases with higher occupant risk values are necessary to more fully describe the relation between flail space criteria and occupant injury. Figure 69 presents the distribution of longitudinal occupant impact velocities and occupant ridedown accelerations for the cases that have an estimate for both measures (i.e. 58 cases). An examination of this figure indicates a majority of the cases available for analysis have occupant impact velocity and occupant ridedown accelerations below the NCHRP 350 maximum longitudinal thresholds of 12 m/s and 20 G, respectively. As the cases above the thresholds are expected to produce more severe injury, these cases are critical to the assessment of how well the flail space model correlates to actual occupant injury.

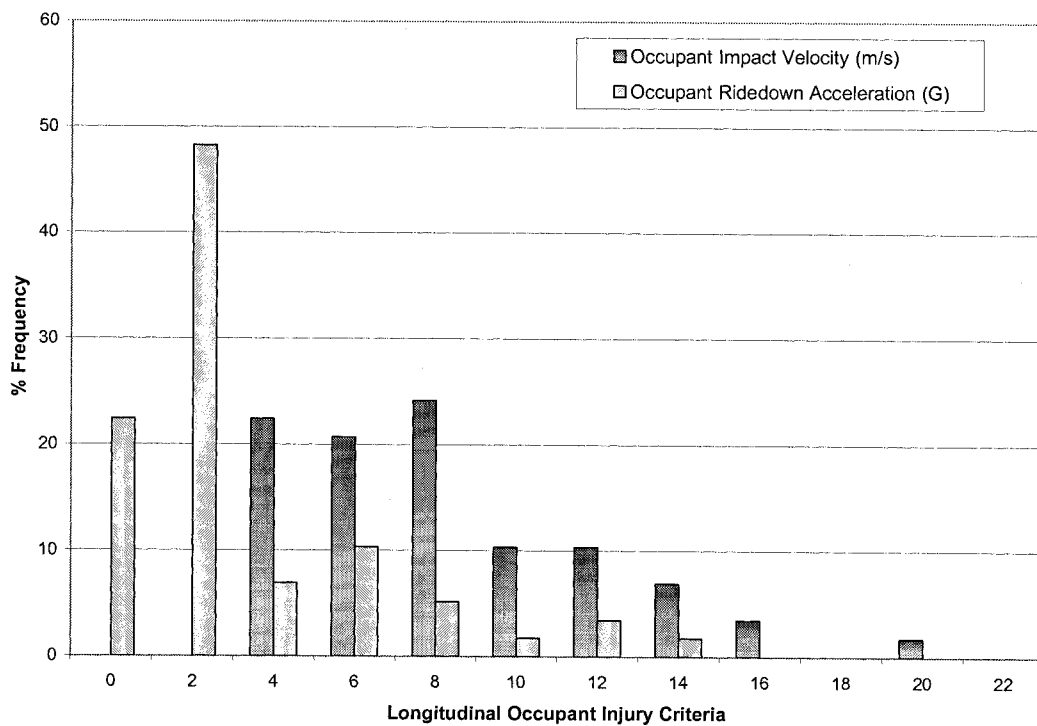


Figure 69. Distribution of Longitudinal Occupant Impact Criteria

5.3 Absence of Lateral Information

A complete analysis of the linkage between the flail space model and actual occupant injury requires data pertaining to the lateral motion of the vehicle. Since the GM EDR is only capable of recording vehicular velocity changes in the longitudinal direction (parallel to the typical vehicle direction of travel), this study is strictly limited to frontal collisions. Although this allows an evaluation of the applicability of the longitudinal thresholds of the model, no information can be deduced regarding the validity of the lateral limits. According to Snyder [16], there is limited information regarding the effects of lateral impacts on the human anatomy in comparison to the data available for forward-facing impacts. Thus, the investigation of the lateral limits of the flail space model is critical since these values have been based on a less extensive research base.

In addition to providing a comprehensive analysis of the flail space model, the inclusion of the lateral facet is vital to the investigation of roadside hardware collisions. Typically, these collisions involve both lateral and longitudinal changes in vehicle velocity; the most obvious example is an oblique collision with a longitudinal barrier such as a guardrail or concrete median barrier. The lack of the lateral component precludes a comprehensive examination of these important roadside hardware collisions using the GM EDR data. Furthermore, as a testament to the lack of understanding of the injury mechanisms in oblique collisions, ATDs used in automotive industry crash tests have been validated for either frontal or side impacts but not for use in oblique impacts [26]. As such, additional research in this area is necessary.

5.4 Occupant Ridedown Acceleration Computation

Since the GM EDR records velocity only at discrete points, a numerical derivative is required to obtain acceleration values for the computation of the occupant ridedown acceleration. The estimation of the continuous velocity function by the sampling of discrete points, however, may result in degraded information regarding the slope of the sampled function. Further complications arise from the relatively coarse GM EDR recording rate of once every ten (10) milliseconds. NCHRP Report 350 specifies that the occupant ridedown acceleration is the largest 10-ms moving average of the vehicle accelerations subsequent to the time of occupant impact with the interior. As the accelerations can only be determined every 10-ms from the GM EDR data, these values are assumed to be the 10-ms averages.

To investigate how the modifications to the intended calculation procedure affect the value of the occupant ridedown acceleration, six (6) NCAP tests were analyzed (refer to Appendix B for further information). A comparison of the GM EDR- calculated ridedown acceleration to the value computed from the more detailed accelerometer information revealed that the GM EDR consistently overestimated the actual quantity by an average of forty (40) percent. Note, however, that this validation only applies to shorter duration impacts into broad, rigid objects. Additional validation of utilizing EDR velocity information for the computation of the occupant ridedown acceleration must be performed for longer duration collisions and those involving narrow and non-rigid objects. Although the overestimated value computed in this study is useful, a more accurate value for the occupant ridedown acceleration is desirable. A better estimate may be possible if a polynomial curve is fit to the individual GM EDR velocity profiles.

Otherwise, a less coarse recording rate or the provision of vehicle acceleration information is required from the GM EDR.

5.5 GM EDR Recording Duration

The GM EDR information available in the database has a total duration of either 150 milliseconds or 300 milliseconds (depending on the EDR model). Although this time range is sufficient to encapsulate most frontal collisions, other collision types such as redirection collisions with longitudinal barriers typically involve longer time durations. Furthermore, for the single event frontal collisions in the database, the mean time to occupant impact with the vehicle interior is approximately 150 milliseconds. As this is at the upper limit for recording duration of a portion of the GM EDR models, approximately thirty-five (35) percent (31 of 89) of the cases have undetermined occupant ridedown acceleration values. Note that there are 89 available single event frontal collisions in the database. Twenty (20) of these cases were eliminated because the pulse was not complete (e.g. did not converge to a constant velocity) and the hypothetical occupant did not contact the vehicle interior; neither the occupant impact velocity or occupant ridedown acceleration is valid in this case. The remaining eleven (11) cases were eliminated only from the occupant ridedown analysis as the pulse was not complete but the hypothetical occupant impacted the interior prior to the termination of the GM EDR velocity information. For longer collisions such as longitudinal barrier impacts, the percentage of undetermined occupant ridedown accelerations is expected to be even larger. Provision of a longer duration recording capability would improve the probability of obtaining an occupant ridedown acceleration as well as promote a better understanding

of the post-impact vehicle trajectory in these typically longer duration roadside hardware collisions.

5.6 Exclusion of Other Vehicle Manufacturers

The Rowan University EDR database only contains information regarding GM vehicles. As occupant injury depends on numerous factors related to the impacting vehicle, a comprehensive analysis of the flail space model should include data from all vehicle manufacturers. Although a large deviation between vehicle manufacturers is not expected, inclusion of a number of vehicle manufacturers will account for any subtle differences in vehicle crashworthiness, vehicle safety restraints, and occupant compartments of different vehicle makes and models.

5.7 Occupant Compartment Intrusion

In addition to the flail space model, the occupant risk criteria prescribed by NCHRP Report 350 also requires that the occupant compartment remain intact during a collision. Since side impacts are not included in this data set, occupant compartment intrusion is not expected to be as likely, although it is possible. This analysis did not control for occupant compartment integrity. Of the 69 cases available for the occupant impact velocity analysis, 43 cases had no intrusion, 15 cases had intrusion, and intrusion was unknown in the remaining 11 cases. For the 15 intrusion cases, minor occupant injury ($\text{MAIS} \leq 2$) was noted in 8 instances while the remaining cases resulted in severe injury (four MAIS 3 values, two MAIS 4 values, and one MAIS 5). Future studies, especially those including impacts other than frontal collisions, should include occupant compartment integrity as a criterion for case selection.

CHAPTER 6 – CONCLUSIONS

In light of the enumerated limitations, the following conclusions are presented based on the comparison between the flail space criteria and actual occupant injury for the suitable cases in the Rowan University EDR Database. The organization is parallel to that of the analysis section; the conclusions regarding the efficacy of the occupant impact velocity are presented followed by the conclusions regarding the occupant ridedown acceleration, and finally, the conclusions regarding the efficacy of the combination of these measures.

6.1 *The Occupant Impact Velocity*

With respect to the injury prediction efficacy of the occupant impact velocity, the following can be concluded:

- In single event frontal collisions, the longitudinal occupant impact velocity is a substantial predictor of overall occupant injury.
- Even though the longitudinal occupant impact velocity threshold values have been based on frontal head impacts with windshields, the occupant impact velocity is a weak predictor of occupant head injury in this data set.
- Occupant impact velocity appears to be a good predictor of chest injury, upper trunk injury and, to a lesser extent, lower extremity injury for single event, frontal collisions.
- For the upper extremity and abdominal body regions, the occupant impact velocity is a weak predictor of injury in this data set.

- No relation between the occupant impact velocity and occupant spine, neck and face injury is evident in this data set.
- The current NCHRP 350 longitudinal occupant impact velocity thresholds appear valid for the analyzed cases, especially for the use in overall occupant injury, chest injury, and upper trunk injury.

6.2 *The Occupant Ridedown Acceleration*

With respect to the injury prediction efficacy of the occupant ridedown acceleration, the following can be concluded:

- The data set contained no occupant ridedown acceleration values in excess of the current thresholds; no conclusions can be drawn.
- No conclusions can be drawn regarding the occupant ridedown acceleration and occupant injury to particular body regions.

6.3 *The Flail Space Model*

With respect to the injury prediction efficacy of the occupant impact velocity in combination with the occupant ridedown acceleration, the following can be concluded:

- In single event frontal collisions, the combination of the flail space criterion appears to be a substantial predictor of overall occupant injury.
- The occupant impact velocity is a more significant predictor of injury in relation to the occupant ridedown acceleration in this data set.
- No conclusions can be drawn regarding the combination of the occupant impact velocity and occupant ridedown acceleration and occupant injury to particular body regions.

6.4 *General Conclusions*

This study has provided a first glimpse at the relation between the flail space model and occupant injury and has established a methodology for future studies. As more data becomes available, these conclusions can be revisited with larger and more representative samples. A better understanding of this relation may lead to an improved injury criteria, or, in the least, enable the roadside safety community to make more informed decisions regarding the implementation of roadside safety hardware on our nation's highway system.

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APPENDIX A – ANNOTATED BIBLIOGRAPHY

A.1 Roadside Safety Hardware Test Procedures

Olson, R.M., Post, E.R., and W.F. MacFarland. *Tentative Service Requirements for Bridge Rail Systems*, NCHRP Report 86, 1970.

The objective of this study is to define service requirements for bridge rail systems as a prelude to established design criteria. To ascertain the current state of the art, nine state transportation departments were visited and consulted. Using state accident information, the authors indicate four hazardous conditions as (1) vehicle penetration of bridge or approach barrier rails, (2) vehicle snagging on components of the bridge or approach rails, (3) vehicle impact with the bridge approach end or approach barrier rails and (4) improper redirection of a vehicle. A simplified mathematical model of a vehicle-barrier railing collision is presented (verified with full-scale crash tests) along with a discussion of tolerable limits of vehicle deceleration. Together, this is used to synthesize a rational approach to the design of bridge barrier rails to aid designers. Ten bridge rail service requirements are presented with commentary to serve as a basis for future development of design guidelines/requirements. Also, information is presented regarding economic analyses of bridge rails.

The discussion of tolerable human deceleration limits focuses on oblique impacts and presents results of the studies to date. Combining a study done by Michalski relating vehicle damage to proportion of vehicles with occupant injury and a study by Garrett reporting vehicle speed and departure angle, the authors indicate that approximately 85 percent of accidents (standard vehicle size) would result in an average of 3G's or less average lateral deceleration. For this level of average deceleration, this study estimates that 85 percent of accidents would not result in fatalities and that 60 percent would not result in injury for unrestrained occupants. These results have been shown to correspond with findings of previous studies (Graham and a study conducted at Cornell Aeronautical Laboratory). See references below:

Michalski, C.S., "Model Vehicle Damage Scale: A Performance Test." *Traffic Safety*, Volume 12, No. 2, June 1968, pp 34-39.

Garrett, J.W., and Tharp, K.J., "Development of Improved Methods for Reduction of Traffic Accidents." *NCHRP Report 79* (1969).

Shoemaker, N.E., "Summary Report of Highway Barrier Analysis and Test Program," *Cornell Aeronautical Laboratory Report No. VJ-1472-V-3*, 1961.

Graham, M.D.; Burnett, W.C.; Gibson, J.L.; and Freer, R.H., "New Highway Barriers, The Practical Application of Theoretical Design," Highway Research Record No. 174, 1969.

Bronstad, M.E. and J.D. Michie. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances*. NCHRP Report No. 153, TRB, National Research Council, Washington, DC, 1974.

This evolutionary document presents standardized procedures for performing full-scale crash tests of roadside appurtenances and served as an update to the original procedures (Highway Research Board Circular #482, 1962). Specifics are included for the installation of the test article, the properties of the test vehicles (2250 lb and 4500 lb car), the speed and impact conditions, and the procedures for data collection. Evaluation of particular piece of hardware is based on three criteria: structural adequacy of the appurtenance, the impact severity, and the vehicle trajectory. As there are an infinite number of crash conditions possible, the approach of these tests is to test the practical worst case scenario rather than the most frequent. Also, to eliminate differences between installation configurations, all appurtenances are installed in a normalized condition (i.e. straight length of need section, relatively flat surface, etc.).

As this report precedes the advent of the flail space model, the occupant risk is assessed based on the impact severity criteria. For redirection collisions ($<15^\circ$ impact angle), this document specifies limits on the longitudinal, lateral and total 50 ms average accelerations of the vehicle (as measured near the center of mass of the vehicle). The acceptable limits are 5 G, 10 G and 12 G for the lateral direction, longitudinal direction, and total, respectively, while the preferred limits are 3 G, 5 G, and 6 G for the lateral direction, longitudinal direction, and total, respectively. For the determination of the "total" category, the guidelines do not provide a concise explanation as to whether this is found by simply by adding the lateral and longitudinal accelerations or by evaluating the resultant accelerations. ATDs are prescribed as optional in these tests and the response must be consistent with the FMVSS 208 (frontal impact) regulations. For crash cushion impacts and guardrail end terminals where the vehicle is decelerated to a stop, the authors recommend a maximum average deceleration of 12 G, with the desirable average acceleration between 6 G and 8 G. For breakaway or yielding sign supports, a maximum momentum change of 1100 lb-s is prescribed. Another important note is the caution expressed by the authors when using the impact severity criteria: "These criteria are not valid, however, for use in predicting occupant injury in real or hypothetical accidents." This appears counter-intuitive since the acceptability of a device is partially contingent upon this criteria; one would expect that it would at least grossly approximate injury in vehicle occupants, otherwise, incorrect decisions regarding the use of roadside hardware could be made.

Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. Transportation Research Circular No. 191, TRB, National Research Council, Washington, DC, February, 1978.

This document served as an interim update to NCHRP Report 153 prior to the adoption of NCHRP Report 230. In 1976, Transportation Research Board (TRB) Committee A2A04 accepted responsibility of reviewing the efficacy of the procedures presented in NCHRP 153 and identified two categories of changes: (1) minor changes to specific problem areas in the report and (2) major, scope-broadening changes. This document represents the results of the minor change category. Changes incorporated into this document include specifics on soil compaction, a more specific description of suitable test vehicles (4500 lb standard or 2250 lb sub-compact), revision of breakaway/yielding support tests to include only sub-compact vehicles, and provisions for the consideration of temporary devices to be installed in work zones.

A majority of the prescribed occupant risk criteria was retained in this update including the redirection criteria based on the 50 ms maximum vehicle acceleration. For the optional anthropomorphic test dummy response, however, the seat belt force criteria were replaced with a limiting femur force value (1400 lb). Also, there are additional details provided for occupant crash tolerance in breakaway/yielding support tests. The procedure is modified so that the momentum change in the low speed test (20 mph) is less than 750 lb-s and the momentum in the high-speed test is less than the original limiting value of 1100 lb-s. A conditional pass for the case where the low speed test momentum change is between 750 and 1100 lb-s; this requires the low speed test to be run again with a momentum change less than 1100 lb-s prior to executing the high-speed test.

J. D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*. NCHRP Report 230, TRB, National Research Council, Washington, D.C., 1981.

Intended as an update to Transportation Research Circular 191, NCHRP Report 153 and HRB Circular 482, this report presents uniform procedures for evaluating the safety performance of candidate roadside hardware. This document represents the efforts of NCHRP Project 22-2(4) in conjunction with an ad hoc panel to address the major scope-broadening changes of NCHRP Report 153 identified by TRB Committee A2A04. Specifics are included for the installation of the test article, the properties of the test vehicles, the speed and impact conditions, and the procedures for data collection. Evaluation of particular piece of hardware is based on three criteria: structural adequacy of the appurtenance, the degree of risk to which a theoretical occupant is subjected, and the post-impact trajectory of the vehicle. The major modifications incorporated into this update include provisions for in-service evaluation of roadside safety features, provisions for testing large vehicles (buses and tractor trailers), and inclusion of the flail space concept for evaluation of occupant risk.

An explanation of the flail space model is provided as a means of estimating the degree of occupant risk in a full-scale vehicle-to-roadside hardware test. Assuming the occupant to be an unrestrained point mass, this model indicates occupant risk level based on two stages of possible injury. First, the unrestrained occupant is thrust forward (in relation to the vehicle) in the event of a collision and strikes the vehicle interior; the

difference in velocity between the occupant and occupant compartment is termed the occupant impact velocity. After impacting the vehicle interior, the occupant is assumed to remain in contact with the interior and subjected to the accelerations of the vehicle subsequent to the time of impact; the maximum 10 ms moving average of the vehicle/occupant accelerations subsequent to the time of occupant impact is termed the occupant ridedown acceleration. Both values are computed using the obtained vehicle acceleration information (from the test) and assuming the vertical acceleration negligible, ignoring the yaw motions of the vehicle, and assuming that the lateral and longitudinal motions of the theoretical occupant are independent. Limiting values and recommended safety factors are presented for both the occupant impact velocity and occupant ridedown acceleration (in both the lateral and longitudinal directions). The inherent assumption of this model is that lower values of these indicators, the lower the potential for occupant injury. A significant stipulation for the use of this criterion is that the test vehicle remains upright during and after the collision and that the occupant compartment is maintained (no intrusion). As with the previous occupant risk evaluation methods, Michie retains the caution that these new evaluation procedures are not valid "...for use in predicting occupant injury in real or hypothetical accidents."

The development of recommended threshold values for the occupant impact velocity and the occupant ridedown acceleration have been based on a small amount of human injury tolerance research and provision of a procedure approximately equivalent to those presented in the previous document (TRC #191). For the occupant impact velocity, 40 feet per second and 30 feet per second are suggested for limits in the longitudinal and lateral directions, respectively. For the occupant ridedown acceleration, 20 G's is suggested as a limit for both the lateral and longitudinal directions.

American Association of State Highway and Transportation Officials. *AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals*. AASHTO, Washington, D.C., 1985.

This document is one in a series of evolutionary documents aimed at prescribing specifications for the supports of highway signs, luminaires, traffic signals, and breakaway supports. Design details are provided with regard to the application of loads, methods of structural analysis, foundation design and detailing. Information is also provided for several materials including aluminum, steel, and prestressed concrete.

NCHRP Report 230 did not specify separate occupant risk criteria for tests involving support structures and work zone traffic devices. This version of the AASHTO standard specification requires that breakaway devices do not produce a vehicular change in velocity greater than fifteen (15) feet per second and preferably ten (10) feet per second or less (for full-scale tests between 20 and 60 miles per hour). For NCHRP Report 350, these limits were adopted for the occupant impact velocity for tests involving breakaway support structures and work zone traffic devices. Note that the limits are not identical, as they have been converted to SI units (5 and 3 meters per second, respectively). This appears to be the only correlation of this document to the flail space model and accompanying limits.

Ross, H.E., Sicking, D. L., Zimmer, R.A., and J.D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. NCHRP Report 350, TRB, National Research Council, Washington, D.C., 1993.

Intended as an update and expansion to NCHRP Report 230, this report presents uniform procedures for evaluating the safety performance of candidate roadside hardware. This document is the result of the efforts of the research team contracted under NCHRP project 22-7. Although the three main evaluation criteria (structural adequacy, occupant risk, and post-impact trajectory) remain, there have been a number of significant changes incorporated in this document. Of particular note is the multi-service level concept that provides six different test levels to allow for more or less stringent performance evaluation (ideally dependant on the ultimate usage/placement of the hardware). Other noteworthy modifications include the conversion to metric units, the use of the $\frac{3}{4}$ ton pickup test vehicle in place of the 4500-pound passenger vehicle, inclusion of supplementary test vehicles (700-kg mini-compact passenger car and the 8000-kg single unit truck), side impact testing guidelines (developed by others), and guidelines for selecting the critical impact for tests involving re-directional hardware.

For the occupant risk criteria, the flail space model concept is retained in this update of the procedures and, in accordance with the remainder of the report; all limiting values have been converted to metric units. Several possible modifications to the flail space model were considered although ultimately not incorporated: (1) positioning the occupant in either the driver or front passenger seat as opposed to the vehicle center of gravity, (2) accounting for yaw motion of the vehicle, and (3) modifying the occupant compartment to be more representative of the actual flail space available. The limiting values for both the occupant impact velocity and occupant ridedown acceleration have been expressed in “preferred” and “maximum” levels. For the occupant impact velocity in either direction, the preferred value is 9 m/s with a maximum permitted value of 12 m/s. For the occupant ridedown acceleration in either direction, the preferred value is 15 Gs with a maximum value of 20 Gs. For tests involving breakaway supports and work zone devices, the occupant impact velocity limits are modified to a preferred value of 3 m/s and maximum value of 5 m/s. Except for the breakaway supports and work zone limiting values, the limiting values are comparable to those presented in NCHRP Report 230. Rationale for essentially retaining these values was consultation with experts in biomechanics as well as review of recent literature.

Ray, Malcolm H., Hargrave, Martin W., Carney, John F. III, and K. Hiranmayee. Side Impact Crash Test and Evaluation Criteria for Roadside Safety Hardware. *Transportation Research Record 1647*, TRB, National Research Council, Washington, D.C., November 1998, pp 97-103.

This paper summarizes the preliminary recommendations for performing roadside hardware side impact crash tests (as presented in Appendix G of NCHRP 350) in light of other side impact crash test procedures, namely NHTSA’s FMVSS 214. Side impact test experience to date is explained with a summary of results of tests with slip-base

luminaires, collapsing luminaires, guardrail breakaway cable terminal, eccentric loader terminal, and the modified eccentric loader terminal. Of particular note is the recommendation of the use of Anthropomorphic Test Dummies (ATDs) for occupant risk evaluation in side impact tests for roadside hardware (in strict contrast to guidelines presented for re-directive crash tests in NCHRP 350). The rationale behind this decision is that the test conditions specified (full broadside angle) is consistent with those specified for vehicle-to-vehicle side impact crash tests (which utilize side impact ATDs). Additional research needs identified by the authors include a validated procedure for accounting for ATD position within in the vehicle (ATD position is difficult to maintain due to the movement of the vehicle), a method for estimating ATD response to identify particular tests that will result in excessive ATD damage, and the relation between intrusion, intrusion rate and occupant injury.

Epperson, B., Bligh, R., and Hayes Ross. *User's Manual – Test Risk Assessment Program (TRAP, Version 2.0)*, Report 7254-1F, FHWA, U.S. Department of Transportation, May 1999.

TRAP is a windows based program used to calculate the occupant risk criteria required in conjunction with full-scale vehicle crash tests of roadside safety hardware. The authors detail how to use the program, the required input parameters, and the output options available. For the computation of the occupant risk, TRAP requires vehicle acceleration as a function of time (a tri-axial accelerometer at the CG or two sets of tri-axial accelerometers along the vehicle longitudinal axis) and vehicle yaw rate as a function of time (yaw angle data can be substituted). All input data and several pertinent calculated outputs could be illustrated in a graphical plot or tabular form. Also, detailed information of all the pull-down menus and toolbars are provided for potential users.

With respect to the flail space model, TRAP has the capability to compute the occupant risk as prescribed by U.S. standards (NCHRP Report 350) or European standards (CEN). For the U.S. criteria, the vehicle accelerations are numerically double integrated (trapezoidal rule) to determine the time of first contact (0.3 m lateral or 0.6 m longitudinal). At the time of first contact, the occupant impact velocity in the x and y directions are computed and the larger value becomes the occupant impact velocity. Subsequent to the time of first impact, a 10 ms moving average of the acceleration information in the x and y directions is computed and the largest values in each direction are reported; the occupant ridedown acceleration is the larger of the two values. A similar procedure is followed for the computation of occupant risk according to the European standards. The CEN, however, requires the use of the resultant velocity (rather than the larger component) when computing the occupant impact velocity and subsequent ridedown acceleration. Also, the CEN considers the yawing motions of the vehicle (U.S. standards assume these to be negligible) and allows the head (occupant) to occupy a position forward of the vehicle center of gravity (NCHRP 350 requires the occupant to be located at the vehicle CG). For the computation of the Acceleration Severity Index (ASI), 50 ms moving averages of the vehicle accelerations in the x, y and z directions are computed and fed through the interaction formula to obtain the maximum value. Although not required by the U.S. or European standards, TRAP also computes the

maximum 50 ms average accelerations in the x, y and z directions as well as the roll, pitch and yaw angles with time and corresponding maximum values (if roll, pitch and yaw rates are input).

A.2 Test Procedure Assessment and Discussion

Mak, K. K., Sicking, D. L., and H.E. Ross. Real-World Impact Conditions for Ran-Off-the-Road Accidents. *Transportation Research Record 1065*, TRB, National Research Council, Washington, D.C., 1986.

Utilizing data from an accident analysis study for sign and light pole collisions (Mak and Mason, 1980) and one involving narrow bridge site collisions (Mak and Calcote, 1983), the authors investigate the distributions of impact speed and impact angle for real-world roadside crashes (approximately 600 cases total) on different functional classes of roadways. For the purpose of this study, impact conditions are simply defined as impact speed for point objects (i.e. poles) and impact speed and angle for longitudinal objects (i.e. guardrails). Results indicate that both the distribution of impact speed and impact angle can be approximated with a gamma distribution (for longitudinal objects the speed and angle are assumed independent of one another). Other impact condition considerations mentioned by the authors include the distribution of area of impact for pole collisions, importance of post-impact vehicle trajectory in re-directive collisions, and the effect of non-tracking vehicles on impact characteristics. Two possible applications of this study are application to the full-scale test matrix (suggesting the multiple service level concept first used in bridge railings and later introduced in the subsequent NCHRP 350 guidelines) and the use in roadside safety hardware benefit-cost modeling procedures.

There is no explicit reference to the flail space model. The impact conditions such as the positioning of the vehicle just prior to impact, the yawing of the vehicle at impact, and the post-impact vehicle trajectory could have a significant effect on occupant risk. In addition to relating the performance of the flail space model to injury attained in accidents similar to crash test configurations, its performance should be evaluated for impact conditions other than the crash test configurations. Questions such as how critical yawing motion is to the propensity for occupant risk may be answered and modifications (if necessary) could be made to include this in the flail space model.

Ray, Malcolm H., Michie, J. D., Hunter, William, and J. Stutts. Analysis of the Risk of Occupant Injury in Second Collisions. *Transportation Research Record 1133*, TRB, National Research Council, 1987, p 17-22.

Investigating the occupant risk in collisions subsequent to an impact with a longitudinal barrier, the authors begin with a discussion of the current (NCHRP 230) criteria for evaluation of the post-impact trajectory of test vehicle. Although the authors suggest a few possible causes for secondary collisions, the focus of the research is to demonstrate that these collisions pose a significant hazard to vehicle occupants rather than to determine causation. Accident data from two states (North Carolina and New

York) is utilized to examine the increased risk associated with secondary collisions. Both databases show that vehicle involvement in a second collision after a smooth redirection by a longitudinal barrier significantly increases the propensity for severe or fatal occupant injury. Using rebound data from another study, the authors demonstrate that redirection onto or across the travelway are not an uncommon occurrence. The authors stress the importance of this portion of the evaluation criteria and encourage the development of methods to minimize roadway intrusions of redirected vehicles.

There is no direct mention of the flail space model, however, the implications of this study are directly related to its assumptions. Inherent to the flail space model is that the most injury producing collision event is the first impact. This study demonstrates, however, that secondary collisions pose a significant risk to occupants. Since these secondary collisions are dependant on individual site characteristics as well as timing (with relation to surrounding traffic), the flail space model cannot be used to estimate occupant risk. Although the flail space model may be a redundant or unnecessary measure in the event of a secondary collision, it should still be indicative of occupant injury. The case of secondary collisions simply stresses the complexity of single vehicle collisions and the importance of the other two evaluation criteria (structural adequacy and post-impact vehicle trajectory).

Ray, Malcolm H., Michie, Jarvis D., Hunter, W.W., and J. Stutts. *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume V: Hazards of the Redirected Car*. FHWA RD-87/100, U.S. Department of Transportation, Washington, D.C., 1987.

This report appears to be the basis for the paper presented in Transportation Research Record 1133, "Analysis of the Risk of Occupant Injury in Second Collisions" by the same authors. Utilizing the same two state databases (New York and North Carolina), the authors investigate the hazards posed to vehicles redirected after impacting the length of need section of a guardrail. The results from the examination of approximately 2400 cases suggest that involvement in a collision subsequent to a barrier redirection increases the potential by up to fivefold for serious or fatal injury. Further research is suggested to determine the impact types that result in poor post-impact vehicle trajectories and the authors suggest a more stringent approach to implementing the vehicle trajectory criteria set forth in NCHRP 230. A more detailed narrative is provided regarding the methodology and conclusions reached in the study.

As all driver fatalities in the database involved a right front impact point (3 unbelted and one unknown restraint usage), the authors attempted to link the fatal injuries to a large flail space. This trend, however, was not present in the incapacitating injuries as a majority of the driver injuries (18 of 26) resulted from a left front impact point. Regardless of these trends, no attempt was made to determine the exact cause of the injury or fatality (this is necessary since most cases involved multiple impacts). Thus, no correlation between the flail space model and occupant injury in longitudinal barriers has been established. Refer to the annotation for the paper by the same authors entitled "Analysis of the Risk of Occupant Injury in Second Collisions" for additional discussion.

Kahane, Charles J. Correlation of NCAP Performance with Fatality Risk in Actual Head-On Collisions. NHTSA Report DOT-HS-808-061, January 1994, Internet Site: <http://www.nhtsa.dot.gov/cars/rules/regrev/evaluate/808061.html>. Accessed 8/20/03.

Kahane examines the relation between vehicle scores based on the National Highway Traffic Safety Administration's (NHTSA) New Car Assessment Program (NCAP) tests and fatality risk in actual vehicular collisions. The data set of eligible cases extracted from the Fatality Analysis Reporting System (FARS) database included two-vehicle frontal collisions where both drivers were belted. Extracted from the FARS data between 1979 and 1991, a total of 396 collisions were selected (a total of 792 vehicles). Note that all these vehicles are either identical or comparable to a vehicle utilized in a previous NCAP test. After adjusting the probability of injury based on other related factors (relative vehicle weight, age and sex of the driver), a statistical analysis revealed a significant correlation between NCAP Head Injury Criterion (HIC), peak femur loading, and peak chest acceleration and fatality risk of belted drivers in actual collisions. Combining all three NCAP criteria into a single composite score yields an excellent correlation; for a collision between two equal weight vehicles (one with "poor" NCAP scores and one with "good" scores), the driver of the "good" performing vehicle has on average of 20 to 25 percent lower risk of fatality. Kahane also indicates that the division between the "good" and "poor" NCAP scores that optimize fatality risk are close to the criteria specified in the Federal Motor Vehicle Safety Standard (FMVSS) 208. Examining the relative improvement of safety of vehicle models from 1979 to 1991, the author concludes that fatality risk for belted drivers in two-vehicle frontal collisions has decreased by 20 to 25 percent (the largest decrease just after 1982).

As this research deals only with vehicle crashworthiness, there is no mention of the flail space model. Development of the correlation between the NCAP injury criterion and actual fatality risk is of some importance as an attempt has been made to equate flail space thresholds with these values. For example, Ray et al. (*Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume IV: The Importance of the Occupant Risk Criteria*) indicated that an occupant impact velocity of 40 fps, the limit suggested by NCHRP 230, produced a HIC value of 1000, which is the threshold required by the vehicle crashworthiness standards. As there is no way of determining the NCAP values for the FARS crashes examined, there has been no attempt to correlate these values to injury. The study simply attempts to investigate whether meeting the NCAP criteria provides for a reduced risk of fatality. In other words, the NCAP would not be useful if a vehicle meeting or exceeding these standards did not provide any additional protection to the occupants. The same argument holds for roadside hardware; the flail space model is not useful unless hardware meeting this criterion provides additional protection to the vehicle occupants compared to hardware that does not meet the criteria.

Durkos, John et al. Breakout Group Discussion D: Assessing and Developing Roadside Hardware. *Transportation Research Circular # 435*, TRB, National Research Council, January 1995, pp. 83-85.

The function of this group was to analyze issues associated with the development, testing, and implementation of roadside safety hardware and to prioritize hardware development needs to encourage new designs. A discussion of relevant issues ensues and includes changes in the vehicle fleet, multiple service level development approach as well as underlying barrier philosophy. Due to the dynamic nature of the vehicle fleet, the group suggests research regarding the effect of ABS on the non-tracking impact problem and how vehicle inertial features change barrier performance. Other research suggestions involve development of recommended installation situations for all NCHRP 350 test levels, identification of scenarios where an arrest strategy is superior to a redirection strategy, investigation of the validity of current crash test evaluation criteria, investigation of benefit to cost implications of right-of-way acquisition, and an assessment of the validity of using the “worst case” test vehicles rather than fleet representative vehicles.

Although there is no specific mention, several issues raised by the authors are directly pertinent to the flail space model. The authors question the validity of the assumption that all occupants are unrestrained and whether the current criteria provide a good measure of occupant risk.

Bligh, Roger. Performance of Current Safety Hardware for NCHRP 350 Vehicles. *Transportation Research Circular 440*, TRB, National Research Council, April 1995, pp. 29-34.

This document highlights potential performance effects the replacement of the 4500S (passenger sedan) test vehicle with the 2000P (¾ ton pickup truck) test vehicle on currently installed roadside safety hardware. A comparison of the characteristics of each vehicle type is presented along with preliminary crash test results with the 2000P test vehicle and other pickup trucks. Assessments drawn from the preliminary crash test data suggests satisfactory performance from breakaway devices, support structures, traffic control devices as well as rigid barriers and bridge rails. The widely used flexible barriers (i.e. w-beam and thrie-beam) have been identified as an area of concern with the 2000P test vehicle due to increased propensity for vaulting and rollover. Further research is proposed to quantify the performance of the 2000P test vehicle with current roadside safety hardware and whether it is representative of the sport-utility vehicle portion of the fleet.

The study appears to suggest that a majority of the longitudinal barrier failures with the 2000P vehicle were a result of vaulting or rolling (i.e. the computation of the occupant risk criteria is not prescribed). No mention is made of any test failing due to the occupant risk criteria. With respect to breakaway devices, small sign supports, and traffic control devices, the authors indicate that the occupant risk should not be a concern (NCHRP 350 decreased the limits for these particular devices).

International Crash Test Standards for Roadside Safety Features. *Transportation Research Circular 451*, TRB, National Research Council, Washington, DC, 1995.

This document summarizes the effort on the part of the United States and Europe to promote harmonization between full-scale crash test evaluation standards for roadside safety hardware. It is a compilation of works that have been prepared for the 1993 TRB Annual Meeting by several different U.S. and European authors. For the European standards, information is presented on the role of European Committee for Normalization (CEN), the basis for development, and the current progress of the standards (they were not finished at this point). With respect to the U.S. procedures, a historical perspective of the evolution of the guidelines is provided and a discussion of the current NCHRP Report 350 standards is presented in light of the previous NCHRP Report 230 guidelines. A particular focus is the comparison of U.S. and European standards in the hopes of promoting more uniform evaluation and implementation procedures.

From the U.S. standards, Hayes Ross provides the prose explaining the current NCHRP Report 350 in light of the previous guidelines. A brief explanation of the retained flail space model is provided along with the “recommended” and “preferred” limits. Ross indicates the increase in the lateral occupant impact velocity and ridedown acceleration limits was a result of a literature review (refers to the *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware* series of reports) and consultation with experts. The European methodology to compute occupant risk involves the computation of the Theoretical Head Impact Velocity (THIV), the Post-Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI). With respect to the flail space model, the THIV is equivalent to the occupant impact velocity while the PHD is equivalent to the occupant ridedown acceleration. The significant difference is the use of the coupled equations of motion (lateral and longitudinal motion is not assumed independent) and the use of the resultant velocity (rather than the lateral and longitudinal velocity handled separately). Proposed threshold values are 9 m/s for the THIV and 20 G for the PHD (this corresponds to the “preferred” threshold for the occupant impact velocity and “maximum” threshold for the occupant ridedown acceleration). The ASI is an additional criterion used to account for occupants utilizing passive restraints (i.e. the occupant motion is closer to that of the vehicle motions). By definition, the ASI is the square root of the sum of the squares of the directional ratios. The directional ratio is simply the maximum 50 ms moving average acceleration in a particular direction (lateral, longitudinal, or vertical) divided by the acceleration tolerance limit imposed for that direction.

Mak, King K., Bligh, Roger P., and Lewis R. Rhodes. Crash Testing and Evaluation of Work Zone Traffic Control Devices. *Transportation Research Record 1650*, TRB, National Research Council, November 1998, pp 45-54.

The purpose of this research is to assess the impact performance of numerous work zone traffic devices to ensure compliance with NCHRP 350. Devices tested include temporary sign supports, portable sign supports, plastic drums, sign substrates for use

with plastic drums, two-piece traffic cones, and vertical panels. A brief description of each device precedes a discussion of the crash test results. Although a majority of the devices tested performed in accordance with NCHRP 350, the following demonstrated unsatisfactory performance: (1) the easel portable sign support, (2) wooden A-frame portable sign support, (3) plywood sign panels for portable sign supports, and (4) plywood and polycarbonate sign substrates (for plastic drums). Note that another paper presents the results for work zone barricades, which was another portion of this research.

Initially, the test vehicles were instrumented for the determination of the occupant risk criteria based on the flail space model. The authors found, however, that tests with these devices result in values significantly less than the prescribed NCHRP 350 limits (in this case, the limits are 5 m/s for the occupant impact velocity and 20 G for the occupant ridedown acceleration). As such, the later tests performed as part of this research did not utilize instrumented vehicles and, as a result, the occupant risk criteria were not evaluated.

Thomson, Robert. Roadside Safety Design Philosophies: Are They Working? Traffic Safety on Two Continents, Malmo, Sweden, September 1999.

Thomson examines the hardware design and test criteria utilized in the United States and Europe with the purpose of identifying possible areas of improvement. While there has been a significant improvement in roadside safety, current accident statistics suggest that the fatality rate is asymptotic towards a non-zero value indicating diminishing returns. As such, the criteria for design and testing must be examined more closely to promote additional improvements in safety. Specifically examined are the vehicle impact conditions, vehicle redirection criteria, and occupant risk evaluation procedures. With regard to impact conditions, it is suggested that the current vehicle speed and angle combinations may be conservative. One possible remedy noted would be to tailor the impact conditions based on the intended location of a particular device (i.e. a guardrail serving as a median barrier may be subject to a significant amount of higher speed but lower angle collisions as it is typically closer to the traveled way). In terms of vehicle redirection, several research efforts are cited suggest that the vague current criteria may be limiting safety improvements. Secondary impacts occurring after a successful redirection appear to pose a much greater risk to vehicle occupants.

With respect to the occupant risk criteria, the author provides a brief description of the flail space concept and indicates that, contrary to other portions of the evaluation criteria, the flail space has not accounted for a changing vehicle fleet (i.e. airbags, belt usage rates). Reference is made to the studies done by Council/Stewart and Ray et al. but the author indicates that the model cannot be criticized until a better correlation between the model and actual injury is realized. A suggestion is made to further exploit the usage of computer simulation for occupant risk analysis. Results are presented for a MADYMO based multi-body simulation using vehicle accelerations recorded in actual crash tests as a basis for the prediction of injury. Thomson suggests that the current flail space criteria may be overly conservative and that more detailed simulation modeling or ATDs may allow for more optimum hardware designs.

Mak, King K., Bligh, Roger P., and L.I. Griffin. *Improvement of the Procedures for the Safety Performance Evaluation of Roadside Features*. NCHRP Project 22-14 Final Report, TRB, National Research Council, Washington, D.C., 2000.

The aim of this research effort was to develop a methodology to assess the relevance and efficacy of the current NCHRP 350 testing procedures and to evaluate the need for updating them. With input from a myriad of the roadside safety community, the project panel chose seven areas of focus: (1) test vehicles and specifications, (2) impact conditions, (3) critical impact point, (4) efficacy of the flail space model, (5) soil type/condition, (6) test documentation, and (7) working width measurement. Recommendations in each area are presented in separate white papers in the appendices. Changes eminent in the subsequent procedural document include the adoption of the slightly more generalized CEN version of the flail space model, new critical impact point determinations for transitions, a measurement of soil properties for every new batch of soil, more specific reporting requirements, and inclusion of the working width indication. In order to solicit data required for a better assessment of these testing requirements, the research team has suggested five research studies. These include a determination of the distributions of impact conditions, in-service performance evaluation of roadside hardware, performance limits of roadside hardware, relationships of injury severity to impact conditions, and relationships of injury severity to crash test evaluation criteria.

A thorough investigation of the flail space model is presented with the intention of recommending possible improvements. The authors discuss the evolution and assumptions of the flail space model, the possible errors incurred by the assumptions inherent to the model, and a summation of the model variations to date. Particular attention is given to the European version of the flail space model (CEN); the major differences include the use of the resultant velocity for the occupant impact velocity and subsequent ridedown acceleration, consideration of vehicle yaw motions, and the inclusion of an acceleration severity measure. For purposes of updating the current procedures, the authors considered instrumented anthropomorphic test dummies (ATDs) and crash victim simulators. Although the ATDs could provide a better estimation of occupant risk, limitations such as cost, repeatability of tests, and the lack of any models validated for oblique impacts prohibit the possibility of inclusion of this option in the NCHRP 350 update. The authors also present a description of the state of the art in computer simulations with descriptions of the capabilities and limitations of ATB, MADYMO, and LS-DYNA3D. Recommendations are to adopt the CEN version of the flail space model until sufficient research and development has occurred to implement computer simulation methods for assessing occupant risk in roadside hardware vehicle crash tests.

A.3 The Flail Space Model, Variations and Validation

Michie, Jarvis D. Collision Risk Assessment Based on Occupant Flail-Space Model. *Transportation Research Record* 796, TRB, National Research Council, Washington, D.C., November 1981, pp 1-9.

Michie formally presents the flail space concept for evaluation of occupant risk in roadside hardware crash tests. He provides a brief synopsis of the evolution of crash test occupant risk evaluation to date and explains the need for an update to the TRC #191 methodology. For the proposed flail space method, the occupant is assumed to be an unrestrained point mass located at the center of mass of the vehicle with 0.6 meters of movement permitted in the forward (longitudinal) direction and 0.3 meters movement permitted in either lateral direction. As the possible injury mechanisms in a crash are impact related and dynamic force related, the occupant risk is based on the calculation of two criteria: occupant impact velocity and ridedown acceleration. For the direction (lateral or longitudinal) that reaches the respective flail space limit first, the theoretical occupant impact velocity is found by integrating the vehicular acceleration profile up to the time of impact. Note that the occupant position function (to determine the time at which the occupant travels a given distance) is found by integrating the vehicular acceleration profile twice. Subsequent to the time of occupant impact, the ridedown acceleration is the highest of all 10-ms average acceleration values. Both the occupant impact velocity and ridedown acceleration values are compared to threshold values to determine roadside hardware acceptability in terms of occupant risk. For ease of calculation, all vertical accelerations are assumed negligible, lateral and longitudinal movements are treated independently, and the idealized occupant is assumed to remain in tact with the vehicle interior after the initial collision with the interior. Other assumptions inherent to the model include a non-intrusive impact (with respect to the occupant compartment) and the use of the 50th percentile male in a normal, upright position to determine “flail” distances. Similar to vehicular crash test requirements, the target threshold values for roadside hardware are set so that the injury produced, although serious, is not life threatening (between AIS 3 and 4). A brief discussion of the dynamic forces that produce human injury is presented along with a tabulation of results from studies in this field. Based on the discussion, Michie suggests the following threshold values: 12 m/s for longitudinal impact velocity, 9 m/s for lateral impact velocity, and 15 g’s for the ridedown acceleration.

Ray, M. H., Michie, J.D., and M. Hargrave. Events That Produce Occupant Injury in Longitudinal Barrier Accidents. *Transportation Research Record* 1065, TRB, National Research Council, Washington, D.C., 1986, pp. 70-75.

By analyzing performed sled tests, accident data, and full-scale crash tests, the authors attempt to gain a better understanding of the mechanism of injury in longitudinal barrier impacts. Previous design of longitudinal barriers has been governed by two basic assumptions: (1) occupant risk is highest in the first collision due to the presence of the greatest speeds and forces and (2) the occupant injury is directly related to the intensity of the vehicle collision accelerations. Findings in this paper suggest that severe longitudinal

barrier impact conditions do not typically produce severely injured occupants and that vehicle trajectory and stability subsequent to the collision are major factors in the cause of occupant injury. Likewise, it is suggested that smooth redirection of an impacting vehicle is a more effective means of reducing occupant injury than attempting to limit vehicle accelerations. Note that these results were based on a slender 7 sled tests with instrumented anthropomorphic test dummies (3 frontal and 4 side impacts), a total of 165 longitudinal barrier accident cases (26 from a narrow bridge study by Mak et al. and 139 from LBSS), and 15 full-scale crash tests of bridge railings.

A brief background of the evaluation of occupant risk in roadside crash tests is presented along with an explanation of the recently (at that time) adopted flail space model. The authors point out that there is a lack of data to support the establishment of lateral and longitudinal impact velocity thresholds as well as typical “flail” dimensions. To ensure a more accurate theoretical vehicle interior, the authors measured the interiors of passenger sedans (model year 1978 to 1984) and concluded that the NCHRP Report 230 “flail” space recommendations (2 feet longitudinal and 1 foot lateral) are reasonable. Also, the sled tests supported the hypothesis that an unrestrained occupant behaves as a “free-missile” in the event of a collision as the measured ATD impact velocities were consistent with those computed using the flail space model. Note, however, that the flail space computations utilized the actual flail distance of the ATD in the sled test rather than the typical value recommended by NCHRP 230. An effort was made to correlate the occupant impact velocities as determined by the flail space model to the criteria prescribed by FMVSS 208; the authors concluded that the lateral occupant impact velocity threshold might be overly conservative. By reconstructing 17 longitudinal barrier accidents that produced severe occupant injury, the authors found that the first impact was not the cause of the serious injury in any case. The overall conclusion of the paper is that although the flail space model is a useful tool for the estimation of occupant risk, it does not appear to be a discerning factor in redirectional crash tests.

Ray, Malcolm H., Michie, J. D., and M.W. Hargrave. Occupant Risk in Longitudinal Barrier Collisions. *Conference Proceedings on the Effectiveness of Highway Safety Improvements*, ASCE, 1986, p 283-292.

Traditionally, the design of roadside safety features has been based on the assumption that occupant injury severity is directly related to the intensity of the first collision; as such, the intent has been to design features that minimize lateral and longitudinal vehicular accelerations. This paper investigates the validity of this assumption using sled test experiments, full-scale crash tests, and in-depth accident data. As the lateral component of a redirectional collision is typically critical, four side impact sled tests were performed for various total velocity changes and the Thoracic Trauma Index (TTI) and Head Injury Criteria (HIC) was calculated for each test. The results indicated a remote chance of occupant injury (based on HIC and TTI) for 50 ms average acceleration values up to 18 G's. Full-scale crash tests with bridge rails were investigated (as these are considered the most hazardous of longitudinal barriers) to ascertain typical occupant risk values and acceleration values. For the fifteen investigated crash tests, all the average acceleration values were below 18 G's and the

occupant impact velocity was below 25 fps (the value obtained from the most severe sled test). Reconstructing twenty-five cases from a Texas narrow bridge study (Calcote and Mak, 1983), the authors indicate that the maximum Abbreviated Injury Severity (AIS) value is three (3) for first collisions. These results suggest that if a vehicle remains upright and is smoothly redirected to a stop, the occupants are not typically injured regardless of the intensity of the collision. A significant amount of guardrail collisions that result in severe injury appear to be those where the vehicle is redirected into another roadside object resulting in a more serious collision event.

This paper appears related to the research presented in Transportation Research Record entitled “Events That Produce Occupant Injury in Longitudinal Barrier Accidents”. The conclusion of the similar study was that the occupant risk criterion, although simple to calculate, is typically a redundant indication of occupant risk. Although not specifically stated, the results of this study appear to hint at the same conclusion. All data obtained suggests that ensuring proper redirection without snagging and subsequent collisions is more critical than reducing the severity of the lateral vehicle accelerations and decreasing the lateral occupant risk criteria.

Ray, M. H., Michie, J. D., and L.R. Calcote. *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume III: Evaluating Pre-Report 230 Crash Tests*. FHWA RD-87/098, U.S. Department of Transportation, Washington, D.C., 1987.

Part of a six-volume set intended to identify and investigate the facets of NCHRP Report 230 that require additional research, this report presents methods of re-evaluating pre-Report 230 test results in light of the current Report 230 criteria. Specifically, the authors present methods for converting non-standard data acquisition procedures to NCHRP standards and calculating the occupant risk factor with and without known vehicle accelerations. Examining data from a guardrail terminal test and a crash cushion test, the authors examine the effect of using different filter classes. The authors conclude from this analysis that filtering has only a limited effect on the calculated criteria needed to evaluate a vehicle to roadside hardware crash test. For the case where vehicular accelerations are not known, the authors present a method to obtain a gross estimate of occupant risk with only the impact speed, impact angle, and behavior of the barrier. This model is based on a method developed by Hirsch to estimate exit velocities, average lateral and longitudinal accelerations, and interaction time using only the behavior of the barrier. To determine the level of accuracy of this approximation, the authors compared the “gross” occupant risk values with those obtained from measured vehicular accelerations for 16 roadside hardware tests; the authors reported errors between 0 and 25 percent. The authors warn that this is an appropriate surrogate only in the event that none of the assumptions are violated.

For the case where the vehicular accelerations have been measured, the authors provide a modified version of the flail space method (used at Southwest Research Institute). The main enhancements to the original flail space model (as presented by Michie) is the consideration of coupled motion (lateral and longitudinal), placement of

the occupant at a position other than the center of gravity of the vehicle, and the consideration of the yaw motions of the vehicle during the event. Although the occupant can be placed at a location other than the vehicle center of gravity, it appears that the authors have retained the 2-foot longitudinal and 1-foot lateral flail space limit for the idealized occupant. Two guardrail tests (one smooth redirection and one with sever vehicle snagging) were chosen by the authors to investigate the effects of considering vehicle yaw in the computation of occupant risk. For each case, the error resulting from neglecting the yaw motion was less than 6 percent. One possible explanation for the small discrepancy is that the occupant contacts the interior of the vehicle prior to the yaw rates becoming significant in the collision.

Ray, M. H., Michie, Jarvis D., Hunter, W.W. and J. Stutts. *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume IV: The Importance of the Occupant Risk Criteria*. FHWA RD-87/099, U.S. Department of Transportation, Washington, D.C., 1987.

The fourth in a series of six reports intended to provide additional insight to the NCHRP 230 guidelines, this report specifically investigates the flail space model. This report appears to be the basis for the Transportation Research Publication entitled "Events That Produce Occupant Injury in Longitudinal Barrier Accidents" (Record #1065) and the ASCE Conference proceedings entitled "Occupant Risk in Longitudinal Barrier Collisions"; reference should be made to these annotations for additional discussion. Study results are based on a series of side and frontal impact sled tests with anthropomorphic test devices (ATDs), an analysis of accident data, and an analysis of full-scale crash tests with bridge rails. For the sled tests and survey of vehicle interiors, additional data and narratives regarding methodology are presented in the two appendices.

From the perspective of the flail space model, the purpose of this research was two-fold: (1) investigate the validity of the flail space concept, and (2) attempt to link this criterion to actual occupant injury. A comparison of the actual ATD impact velocity with the value calculated using the flail space model supported the assumption that an unrestrained occupant acts as a "free-missile" within the occupant compartment. Another interesting result of the longitudinal sled tests is that each ATD struck the windshield headfirst; suggesting that a longitudinal criterion based on head injury is suitable. Note that both of these findings are based on an unrestrained occupant. Also, this study found, from an analysis of vehicle interior dimensions (model year 1978 to 1984), that the suggested flail space dimensions set forth in NCHRP 230 are appropriate. For a correlation to occupant injury, the ATD response to the collision was compared to the flail space occupant risk value (occupant impact velocity). A 40 fps occupant impact velocity (limiting value established by NCHRP 230 prior to application of the safety factor) appeared to coincide with a Head Injury Criterion (HIC) value of 1000, which is the current FMVSS 208 limit. With respect to the lateral flail space limits, the side impact sled tests indicated that this criteria may be overly conservative as a 25 fps occupant impact velocity corresponded to a mild 316 HIC and a relatively low Thoracic Trauma Index (TTI) of 113 (16% probability of AIS 3 injury or greater). An analysis of

accident data suggests that a secondary impact subsequent to redirection by a longitudinal barrier expose occupants to a higher potential for injury. A detailed reconstruction of 17 longitudinal barrier collisions indicates that severe occupant injuries (>AIS 4) occur at lateral occupant impact velocities exceeding 40 fps (NCHRP 230 limit is 30 fps). The authors conclude that the flail space model, although a discerning factor for longitudinal impacts, is a redundant measure of occupant risk in redirection tests (if the vehicle is smoothly redirected and remains upright). Recommendations include an elimination of the occupant risk criteria for redirection tests or an increase in the lateral occupant impact velocity threshold from 20 fps to 30 fps.

Ross, H. E., Perera, H. S., Sicking, D. L., and R.P. Bligh. *Roadside Safety Design for Small Vehicles*. NCHRP Report 318, TRB, National Research Council, Washington, D.C., 1988.

As most safety hardware has been designed for passenger vehicles in excess of 1800 pounds and there has been a general trend toward lighter more fuel-efficient vehicles, there is a necessity to evaluate the performance of roadside safety devices with respect to these lighter vehicles. The objectives of this study were to evaluate the performance of various safety features for a 1500-pound test vehicle (with respect to NCHRP Report 230 guidelines) and identify potential modifications to these devices to enable satisfactory performance for vehicles weighing as little as 1250 pounds. Using full-scale crash tests and various computer simulations, the research team evaluated a rigid and flexible longitudinal barrier, breakaway luminaire supports, breakaway and base-bending sign supports, crash cushions, guardrail terminals, and several roadside features including slopes, driveways and curbs.

The flail space model (as prescribed in NCHRP 230) was used to evaluate occupant risk in the roadside hardware tests using the small vehicles. For the purposes of comparison, a variation of the flail space model has been generated to more accurately represent the motion of an unrestrained occupant within the occupant compartment. The revised version provides a more exact representation of the occupant compartment (i.e. the driver is allowed to “flail” a greater distance to the right), accounts for any angular acceleration of the vehicle, and does not treat lateral and longitudinal movements of the occupant independently. Note that this revised model is only used in the simulated crash tests (run using HVOSM). For the simulation runs, the occupant impact velocity in the lateral and longitudinal directions is computed using both the flail space model (as prescribed by NCHRP 230) and the revised version presented by the authors. Both of these values are then compared to the lateral and longitudinal impact velocities determined from the corresponding full-scale crash tests. Results indicated overall good correspondence between the occupant impact velocities obtained from full-scale crash tests and the occupant impact velocities obtained from the corresponding simulations. Also of note is the propensity for the revised method to produce more critical occupant impact velocities, especially in the lateral direction where every value was greater than that obtained by the original flail space model.

Hinch, J. et al. Impact Attenuators: A Current Engineering Evaluation. *Transportation Research Record 1198*, TRB, National Research Council, Washington, D.C., 1988.

Sponsored by the Federal Highway Administration (FHWA), this research employed full-scale crash tests to investigate the performance of inertial type and energy absorbing impact attenuator systems. The specific focus is to investigate the performance of compact cars in impact attenuator collisions, determine problems associated with frozen sand in inertial attenuators, and investigate performance of inertial attenuators using different fill materials and techniques. A total of 20 full-scale tests were conducted in accordance with NCHRP 230 guidelines: 16 with inertial attenuators and 4 with the Guard Rail Energy Absorbing Terminal (GREAT). Conclusions drawn from the inertial system tests include acceptable performance of systems with non-frozen sand, unacceptable performance of systems with frozen sand due to a shift of the hard point and possibility of frozen block launching, unacceptable performance of bagged sand systems due to the increased propensity of launching and intrusion of sand bags into the occupant compartment, and unacceptable performance of the pea-gravel systems due to the ball-bearing effect of the gravel on the roadway. With regard to the GREAT system, all tests but the 4500 lb head on test were acceptable.

Occupant risk in each test was evaluated using the vehicle-based roadside criteria as well as the NHTSA instrumented anthropomorphic test device approach. For the instrumented test devices, the following values are computed: Head Injury Criterion (HIC), Chest Severity Index (CSI), maximum chest acceleration, and maximum right and left femur loads. Note that nineteen of the twenty tests were within the current limits for the values derived from the instrumented test dummies. For the roadside-based criteria, the following values are computed: average acceleration to stop the vehicle, fifty millisecond peak acceleration, occupant impact velocity using NCHRP 230 two foot flail distance, occupant impact velocity using the actual flail distance, and the occupant ridedown acceleration. Thirteen of the twenty tests exceeded the NCHRP 230 “recommended” threshold limits while only four exceeded the “maximum” threshold values. In light of these results, the authors suggest that the “recommended” design criteria may be too conservative. The authors also attempted to determine correlations between the obtained test data. A good correlation ($r > 0.8$) was found between 50 ms acceleration and 10 ms ridedown acceleration as well as occupant impact velocity using the NCHRP 230 two-foot flail distance and occupant impact velocity using the measured flail distance. To a lesser extent, correlations were observed between occupant impact velocity using two-foot flail distance and the following: (1) HIC, (2) CSI, and (3) maximum chest acceleration. No further details are provided on the type of correlations encountered.

Ray, M. H. and J.F. Carney. Improved Method for Determining Vehicle and Occupant Kinematics in Full-Scale Crash Tests. *Transportation Research Record 1233*, TRB, National Research Council, Washington, D.C., 1989.

The purpose of this paper is to investigate the effects of the assumptions made in the flail space model, assess them in terms of the impact on the results, and derive and implement alternative procedures in the form of reusable program. A brief timeline of suggested improvements to the flail space model is provided along with the authors' rendition of the flail space model as originally prescribed in NCHRP 230. Indicating that the original formulation of the flail space model neglects several significant physical effects, the authors explore the sensitivity of transducer position, the effect of treating the lateral and longitudinal movements of the unrestrained occupant independently, and the effect of vehicle rotation on occupant impact velocity. For the sensitivity to the location of the transducers, a derivation (from elementary dynamics) is presented to correct for transducers not placed at the vehicle center of gravity; the conclusion is that a transducer located within 12 inches of the actual vehicle center of mass can cause a 10 percent error in the measured acceleration values. For the lateral and longitudinal motion independence assumption, a derivation is included for the coupled equations of motion followed by a demonstration of the accuracy of numerical methods to determine a solution. Two redirection crash tests were analyzed to determine the error introduced by assuming independent motion; an approximate error of 5 percent was found in both cases. The authors hypothesized that the error would be greater (on the order of 20 percent) for non-tracking and side impacts. In terms of tracking the orientation of the vehicle and occupant past the initial impact point, the authors found that this has a relatively small change on the initial impact velocity. A description is provided of the program that tracks the location of the occupant as well as the orientation of the vehicle throughout the duration of the event. To determine the position of the occupant subsequent to the first impact, the velocity normal to the boundary is found (at the time of impact) and subtracted from the occupant velocity in that direction.

Council, Forrest M., and J. Richard Stewart. Attempt to Define Relationship between Forces to Crash-Test Vehicles and Occupant Injury in Similar Real-World Crashes. *Transportation Research Record 1419*, TRB, National Research Council, Washington, D.C., 1993.

This paper attempts to explore the relationship between the surrogate measures of occupant risk utilized in full-scale roadside safety device tests and the actual level of injury experienced by occupants in actual crashes. Overall approach methodology consisted of matching instrumented full-scale crash tests with similar vehicle characteristics (make, model and year), crash characteristics (object struck, impact location on vehicle, etc.), and crash severity (as measured by vehicle deformation). For longitudinal and lateral acceleration of momentum change, 223 usable crash tests were linked to 232 suitable vehicle accident records. For occupant ridedown comparison, only 76 suitable crash tests were available to be linked to 62 appropriate vehicle accident records. Contingency table analysis and logistic regression modeling were used to investigate any possible relationships between the surrogate and actual injury levels. No strong correlation was found between lateral and longitudinal impact velocity and the results of the ridedown acceleration investigation were even less fruitful. The investigation of change in momentum, however, displayed a stronger correlation to subsequent occupant injury. Data limitations are cited as the biggest obstacle to this

research; the authors suggest a wider spectrum of speed and impact angles in vehicle crash tests, a more accurate measure of impact velocity and impact angle in accident databases, and a larger representative data set.

Evolution of occupant risk evaluation in vehicle-to-roadside crash tests is provided up to and including the flail space model. The authors stress the importance of the development of a relationship between crash test forces and actual occupant injury and indicate that there has been virtually no accident-based evaluation of any of the three predecessors of the flail space model or the efficacy of the flail space model itself. Ideally, recognition of the relationship would facilitate proper decisions regarding the acceptance/rejection of roadside safety hardware, meaningful crash-test based hardware design changes as well as potential development of more accurate severity indexes for roadside features. With respect to improvement of the flail space model, the authors suggest development of a flail space measure for a driver in an offside impact as well as combining longitudinal/lateral occupant impact with lateral/longitudinal ridedown to produce a more predictive measure. The authors conclude that there is still a clear need to determine how surrogate measures of occupant risk relate to actual human injury sustained in real crashes.

A.4 Human Injury Tolerance Research

Gadd, Charles. Use of a Weighted-Impulse Criterion for Estimating Injury Hazard. *Proceedings of the 10th Stapp Car Crash Conference*, Paper 660793, November 8-9, 1966.

Gadd explains a method for assessing the injury severity potential of deceleration or force impulses by utilizing an exponential weighted integration approach. Although this method can be applied to any body part (with proper validation), this paper deals specifically on frontal head impacts. Previous methods at evaluating the severity in terms of injury have focused on a particular facet of the pulse (i.e. peak acceleration, integral of the pulse, and rate of change of acceleration). Unlike the previous methods, the method proposed is based on the premise that injury is both a function of intensity and duration. The severity index is a single numerical value computed by integrating an exponentially weighted pulse (either acceleration, force, or pressure) with respect to time. This value can then be used to compare different tests to ascertain relative severity or for estimation of whether an impact exceeds a safe threshold value. Another important aspect of this method is its applicability to a waveform of any type. From other research at Wayne State University and Eiband at NASA, Gadd estimates the weighting factor for head injuries to be approximately 2.5. He also discusses development of appropriate indices for the face as well as the chest.

Snyder, R.G., "State-of-the-Art – Human Impact Tolerances," SAE 700398, International Automobile Safety Conference Compendium, May 1970.

Snyder provides a historical perspective on human injury tolerance research in light of known problems and future needs and directions. To date, human volunteers,

clinical accident reports, cadavers, experimental animals, anthropomorphic test devices, accidental free-falls, mathematical models, and developed damage sensitivity curves and injury scales have been utilized to ascertain information regarding human tolerance to impact. A discussion of each methodology is provided with respect to validity of application and inherent limitations. Descriptions of past and present research efforts are presented with respect to the following body regions: head, face, neck, chest, abdominal, and lower extremities. In addition, the author discusses research dealing with whole body impact tolerance in regard to the differing body orientations: forward facing, rearward facing, lateral, and head-ward or foot-ward orientation. Although great strides have been made in this field of research, Snyder indicates that the overall knowledge remains “very general and fragmentary”. Identified problem areas include lateral tolerance limits, effects of off-axis impact on the body (i.e. typically in longitudinal barrier collisions), as well as the effects of regional injuries on the body as an entire system. Tables are provided at the end of the document detailing the impact tolerance studies to date organized by direction of applied force/acceleration/impact and type of test subject.

This comprehensive review of human injury tolerance research and literature is cited in the commentary of NCHRP Report 230 as a basis for the development of the lateral and longitudinal ridedown acceleration thresholds. Also, NCHRP Report 350 cites this work as a foundation for the determination of the arbitrarily conservative 10 ms moving average occupant ridedown acceleration (Note that Snyder indicates injury-producing pulse duration ranges between 7 and 40 ms depending on the body component).

Williams, James S. The Nature of Seat Belt Injuries. *Proceedings of the 14th Stapp Car Crash Conference*, Paper 700896, 1970, pp 44-65.

Williams provides a clinical examination of the injuries associated with seat belts in automobile accidents. Although some cases examined have been previously unreported, the majority of the examined cases were previously reported by other authors. The author estimates fatality would have resulted in a majority of the cases had the occupant not been using a restraining device. Injury patterns are identified by each category of restraint utilized: (1) lap belt only, (2) shoulder belt only, and (3) combination lap and shoulder restraint. The majority of injuries associated with the use of the lap belt are abdominal with some lower lumbar injuries. With respect to the shoulder belt, mostly skeletal injuries to the ribs, sternum, and spine are produced and the occupant is not protected from ejection or submarining in the case where the door opens. The lap and shoulder combination is found to be the most effective restraint type; the most common injuries are fractures of the ribs, clavicle, and sternum. For each body region injured, the author provides some insight into the possible or most frequent mechanism(s) of injury.

There is no mention of the flail space model as this work predates NCHRP Report 230. Since the flail space model predicts injury based on an unrestrained occupant, there is no consideration for injuries caused by utilized restraints. Although Williams

examines the nature and mechanisms of these injuries, no allusion is made to the levels of force or deceleration required to produce injury.

Nordlin, E.F., Woodstrom, J. H., Hackett, R.P., and J. Folsom. Dynamic Tests of the California Type 20 Bridge Barrier Rail. *Highway Research Record* 343, 1971, pp. 57-67.

Nordlin presents the results of five (5) full-scale crash tests of the California type 20 bridge rail. All tests utilized a 4900 lb test vehicle at an impact angle of 7, 15, or 25 degrees, while test speeds ranged between 45 and 66 mph. A description is provided for the barrier design and construction as well as the test vehicle and associated instrumentation utilized in the tests. The test results suggest that this sloped barrier provides added protection for occupants when impacted at shallow angles since the vehicle tire/suspension absorbs some of the energy and the redirection angle is quite small. With larger impact angles (>10 degrees), however, the barrier offers no performance advantage over other non-sloped rail designs used at the time.

With respect to occupant injury, this research utilizes the threshold values first suggested by Shoemaker, who is attributed as the first to attempt to establish human injury tolerance based on vehicle dynamics during a longitudinal barrier collision. All five tests are evaluated using the criteria (highest 50 ms deceleration limits for unrestrained, lap belt-restrained, and lap and shoulder belt-restrained occupant) set by Shoemaker to determine occupant risk. Based on this analysis, impact angles less than seven degrees will produce little or no injury regardless of restraint while a 65 mph impact at 25 degrees will produce severe injuries for unrestrained occupants and no more than moderate injuries if a lap and shoulder belt are utilized.

Kay, S.E., Pickard, J., and L.M. Patrick. Improved Laminated Windshield with Reduced Laceration Properties. *Proceedings of the 17th Stapp Car Crash Conference*, Paper 730969, 1973.

The authors present the results of the testing of an improved windshield design, “ten-twenty”, with reduced laceration properties. An evaluation of the performance of this new windshield was based on results of dropping head-form tests and skull impactor tests performed by the manufacturer; and sled tests using a 50th percentile male anthropomorphic test device (ATD) performed at Wayne State University (WSU). Test results include impacts up to 60 km/hr (16.7 m/s) and are expressed in terms of the Head Injury Criterion (HIC), Gadd Severity Index (GSI) and the Triplex Laceration Index (TLI). Although there were some observed differences between the tests at either location, the general consensus was that the “ten-twenty” windshield provided reduced laceration properties without a significant increase in occupant head injury potential. Other added benefits of this product are discussed and include a greater resistance to breakage due to stone impact, smaller potential for crazing in the event of a stone impact, and reduced potential for breakage during fabrication and handling.

In terms of the flail space model, the ATD tests in this work are cited in NCHRP 230 as a basis for the development of the threshold limits for the longitudinal occupant impact velocity. Although a total of 59 sled tests were performed, several had to be eliminated for various reasons (ATD head hit the visor or header or there was significant windshield pullout). The result was a total of 38 sled test results utilized for the analysis. For the tests run at an initial velocity of approximately 55 km/hr (15 m/s), the highest observed HIC value was just under 700. There was an anomalous HIC value of 811 observed in a test with velocity 32.2 km/hr that was attributed to an extra-strong windshield. Nonetheless, all the observed HIC values were below the threshold of 1000.

Hartman, F., Thomas, C., Foret-Bruno, J., Henry, C., Fayon, A., and C. Tarriere. Occupant Protection in Lateral Impacts. *Proceedings of the 20th Stapp Crash Conference*, Paper 760806, 1976.

The purpose of this research is to further the understanding of occupant injury in lateral impact collisions. A total of 296 lateral impacts obtained from 6 years of French accident data are utilized for the analysis. Selection criteria is based on a resulting occupant trajectory between 2 and 4 o'clock or 8 and 10 o'clock (in any seat) and a few cases where the near-side trajectory is expanded by 1 clock direction at either end and intrusion is present. The authors indicate that the sample is grossly representative of the national distribution but the severity is over represented especially in the vehicle-to-fixed object collisions (~25% of the cases but 34% of fatalities). As such, the information is presented in two categories: (1) vehicle-to-vehicle collisions and (2) vehicle-to-fixed object collisions. Using mean dimensions of vehicles, the authors use a probabilistic method to identify the most impacted point (for both collisions categories) on the struck vehicle for all severity cases and more severe cases ($AIS \geq 3$). Also, a description of injury-related factors is presented for both categories of collisions. An investigation of the frequency and severity of occupant injury by body region reveals an uneven exposure to various body regions (i.e. the skull is injured frequently but not severely while the abdomen is not injured frequently but is typically severe).

Michie cites this work in his formal introduction of the flail space model as well as NCHRP 230 as a basis for the determination of the occupant impact velocity thresholds values. Although general injury tolerance research indicates similar lateral and longitudinal injury tolerances in humans, Michie indicates that this is not apparent based on this work. Hartman indicates that, for vehicle-to-fixed object collisions, injury values of AIS 3 or greater were sustained in lateral collisions with a delta-V of at least 30 fps (~ 9 m/s). Also, using a 400 mm diameter pole as the impacted object, the most impacted point for vehicle-to-object collisions is 20 cm forward of the roof high point in a direction such that the occupant trajectory is between 48 and 75 degrees. Note that these conclusions are based on 6 years of French accident data collected from 1970 forward; thus, the vehicle structures, restraint usage and roadside objects are not representative.

Chi, Michael. *Assessment of Injury Criteria in Roadside Barrier Tests*. Report FHWA-RD-75-74. FHWA, U.S. Department of Transportation, Washington, D.C., 1976.

Chi provides a historical perspective on the current state-of-the-art procedures used to evaluate occupant risk in roadside barrier crash tests. With respect to the evolutionary document prescribing test procedures for full-scale roadside hardware tests, this critical review covers procedures up to NCHRP Report 153. In light of the research, the author suggests a more rational approach to evaluating occupant risk utilizing average deceleration and the velocity change up to the instant of "secondary impact" (i.e. the occupant impacts the interior of the vehicle).

Although this review work predates the inception of the flail space model, it appears to echo many of the critical elements of the flail space model. A discussion of human injury mechanisms identifies three major contributors: (1) impact, (2) dynamic force, and (3) hydraulic force. For the impact mechanism, the load time is much shorter than the natural period of the body and the injury is simply dependant on the change in velocity. For longer duration loading, however, the magnitude of the "force" or deceleration acting on the body becomes important (typically measured in gravitational units); this is termed the dynamic force mechanism. In a much longer duration loading (i.e. minutes or more), the injury mechanism shifts to a hydraulic phenomenon where the bodily fluids have sufficient time to overcome viscosity and drain towards the most forward portion of the body (if the body is decelerating). Since automobile collisions are typically less than one second, Chi identifies the impact and dynamic mechanisms as the most critical. He also argues the usefulness of limiting the rate of change vehicle acceleration, or "jolt", in preventing occupant injury (a limiting value of 500 G/s jolt was originally present in the early test procedures). The proposed modification to the injury criteria includes a sensitivity curve approach introduced by Kornhauser and modified by Payne that limits either the change in velocity or average deceleration. Chi suggests that the original either-or approach should be modified to include both restraints as typical barrier collisions have both mechanisms (i.e. the occupant impacting the interior represents a change in velocity while the average deceleration is indicative of restraint or other "deceleration" injuries). Also, the assumption that the occupant acts as a "free-missile" within the occupant compartment appears to originate from this document. Threshold limits for "fatal ore irreversibly disabling injuries" in the longitudinal, lateral, and vertical directions are proposed based on the injury studies to date (note that Chi indicates the relative insignificance of the vertical forces in barrier collisions).

Begeman, P., King, A., Weigt, P., and L.M. Patrick. *Safety Performance of Asymmetric Windshields*. SAE Paper 791009. Society of Automotive Engineers, New York, 1978.

The authors present the results of a comparative study of the performance of asymmetric windshields with differing inner layer thickness (between 0.8 and 1.5 mm) and inter-layer thickness (between 0.76 and 1.14 mm). To facilitate the analysis, two types of tests were performed: vehicle sled tests between 30 and 60 km/hr and headform drop tests between 20 and 30 km/hr. A total of 127 vehicle test runs were made with a

Volkswagen Rabbit and a 50th percentile ATD. The tests indicated that the asymmetric windshields have a lower laceration potential with a decreasing laceration potential as the inner layer thickness and inter-layer thickness decreases. In relation to the Head Injury Criterion (HIC), the asymmetric windshields are comparable to the standard symmetric windshield at speeds greater than 30 km/hr. At lower speeds, the non-fractured asymmetric windshields have lower HIC values than the standard counterparts. As this research aided in the determination of threshold values to be used in conjunction with the flail space model, there is no mention of the flail space model.

Viano, David C., Lau, Ian V., Andrzejak, Dennis V., and Corbin Asbury. Biomechanics of Injury in Lateral Impacts. *Accident Analysis and Prevention*, Vol. 21, No. 6, May 1989, pp.535-551.

Using recent accident data, the authors characterize injury in side impact collisions and identify that approximately half of the fatal injuries involve the chest and abdomen with impact of the side vehicle interior as a contributing factor. As such, this study investigates the mechanisms of chest and abdomen injury and tolerance resulting from blunt lateral impact with the interior of the vehicle. Fourteen swine were subjected to blunt lateral impact (pendulum) with velocities varying from 4.3 to 8.2 m/s. For correlation purposes, the injury response (measured by maximum skeletal and overall AIS value) is compared to several mechanical responses including the viscous response, compression response, peak acceleration (near rib and spine), peak force, and Thoracic Trauma Index (TTI). The tests indicate the best correlation between injury and the viscous response (a function derived by multiplying the instantaneous velocity of deformation and the compression response) although the peak force measure had a better correlation to fatal injury. In addition, the authors indicate a lack of correlation between the maximum deflection and resulting injury as well as between the acceleration criteria and associated fatal injury. Note that previous frontal impact research indicates a positive relation between chest compression and occupant injury. The authors do not dismiss limiting maximum chest deflections stating injury may be a result of a “crushing” mechanism (although it appears that the lateral deflections of the chest may have to be greater to produce injury when compared to frontal deflections).

The authors of NCHRP Report 350 cite this source as a basis for retaining the threshold values for occupant impact and occupant ridedown acceleration prescribed by NCHRP Report 230. Based on this study and the study done by Ray et al (The Importance of the Occupant Risk Criteria), the lateral occupant impact velocity has been increased to 9 m/s match the longitudinal threshold. Note that the lateral impact velocity of 8.2 m/s in this Viano study resulted in a maximum AIS value (for the swine) of 4.40 ± 0.55 ; the original intent of NCHRP Report 230 was to prevent injuries greater than AIS 4.

Severy, D.M. and Mathewson, T.H., “Technical Findings from Automobile Impact Studies,” SAE Transactions, 65, pp 70-83, 1957.

This report presents results from twelve (12) automobile collision experiments with impact speeds ranging from seven (7) to fifty-five (55) miles per hour. The test

spectrum included oblique tests with a bridge rail/curb combination, a single oblique test with a curb, frontal barrier collisions, and rear end collisions. Both human and anthropomorphic test devices (ATDs) were used to investigate aspects of injury minimization. A description of the test instrumentation is provided along with a method to determine the deformation of components obscured from view. Comparison of three tests with identical vehicles and speeds within five (5) mph reveals the difficulty of fixing all but one variable in a full-scale crash test. Consideration of vertical forces in the frontal barrier collisions indicate that these forces tend to be greater towards the end of the event, although no attempt has been made to determine the magnitude and provide a correlation to injury potential. Five (5) occupant restraint scenarios are investigated using the crash tests: (1) no restraint, (2) lap belt only, (3) chest belt, (4) shoulder belt only, and (5) lap and shoulder belt combination. The shoulder and chest restraints are determined superior based on the area under the force-time plots; however, the authors caution that the force concentrations or distributions on the body may prove otherwise. Results from the rear-end collisions indicate that the force on the neck does not correlate with the impact velocity

A.5 Event Data Recorder Technology

Gabler, H.C., Hampton, C., and Roston, T. Estimating Crash Severity: Can Event Data Recorders Replace Crash Reconstruction? *Proceedings of the Eighteenth International Conference on Enhanced Safety of Vehicles*, Paper 490. Nagoya, Japan. May 2003.

The objective of this research is to evaluate the potential for Event Data Recorder (EDR) data to supplement vehicular accident reconstruction. Of particular interest is using EDR data to replace or supplement traditional methods for determining maximum change in vehicle velocity (delta-V) and seat belt usage. A characterization of the Rowan University EDR database is provided along with a description of the capabilities of the GM EDR (225 GM EDR cases populates the database). Comparing the EDR delta-V with the corresponding NASS/CDS estimate (using WinSmash), the authors indicate no evidence that EDR estimates of delta-V deviate from WinSmash estimates. Although EDRs have the potential to provide an estimate of delta-V when there is none estimated by NASS, EDRs do not always record a vehicle velocity history (51% of cases in the database had a zero or missing velocity information). With respect to seat belt usage, a comparison of EDR and NASS/CDS belt usage indication suggests that belt usage may be over reported in NASS/CDS. The authors have identified the following limitations of GM EDR data: (1) insufficient recording times to capture an entire event, (2) inability to capture multiple events, (3) linking EDR data events to those recorded by crash investigators, (4) missing vehicular velocity profiles, (5) provision of velocity information only in the longitudinal direction. Also, an examination of EDR data downloads suggests that the OBD diagnostic connector may not be a reliable download avenue (accounts for 18% of download failures).

APPENDIX B – EDR AND NCAP FLAIL SPACE MODEL COMPARISON

B.1 Objective

The objective is to assess the accuracy of using EDR data to estimate the flail space model parameters needed to indicate the potential for occupant injury. To facilitate this analysis, six (6) New Car Assessment Program (NCAP) tests of GM vehicles are examined. For each test, EDR data has been collected in conjunction with the more precise vehicle acceleration information typical of these tests. A comparison is made between the occupant impact velocity and occupant ridedown acceleration values obtained from each data source.

B.2 Data

Table 10 identifies the NCAP tests examined in the analysis and the corresponding NCAP accelerometer information utilized for the flail space model computations. Note that all tests are 35 mph frontal barrier collisions. For each test, GM EDR data has been obtained using the Vetronix software.

Table 10. NCAP Test Information

NCAP Test Designation	Vehicle (Type)	Accelerometer Designation	Location
4487	Saturn Ion	89	Sill – Left Rear
4472	Chevrolet Silverado	89	Sill – Left Rear
4244	Chevrolet Trailblazer	98	Seat – Left Rear
4198	Saturn VUE 4x4	101	Floorpan – Left Rear
3952	Buick Rendezvous	107	Floorpan – Left Rear
3851	Chevrolet Avalanche 1500	107	Floorpan – Left Rear

B.3 Methodology

B.3.1 Occupant Impact Velocity

Computation of the occupant impact velocity for the NCAP accelerometers follows the procedure outlined in NCHRP Report 350. Since all six NCAP tests examined are frontal barrier tests, computation of the lateral component of the occupant impact velocity is not necessary. Each longitudinal acceleration signal is numerically integrated twice to obtain the position of the occupant compartment as a function of time. Note that the dually integrated signal is filtered with a CFC 180 in accordance with SAE-J211. As the flail space model assumes the occupant to be an unrestrained point mass,

the occupant position with respect to time is computed by multiplying the initial velocity of the vehicle by the elapsed time. The relative position of the occupant with respect to the occupant compartment is then found by taking the difference between the occupant compartment position and the unrestrained occupant position. When the relative position of the occupant reaches the longitudinal flail space limit of 0.6 meters, the theoretical occupant has made contact with the interior of the vehicle. The difference in velocity of the occupant compartment and the occupant at this point in time is the occupant impact velocity.

For the GM EDR data, the computation of the occupant impact velocity utilizes the following relation:

$$0.6 \text{ meters} = \int_0^{t^*} V_x dt$$

The output of the GM EDR is the relative velocity of the occupant with respect to the occupant compartment. To compute the occupant impact velocity, the velocity information is numerically integrated to obtain the occupant position relative to the occupant compartment with respect to time. Linear interpolation is used to determine the time, t^* , at which the relative position of the occupant has reached a value of 0.6 meters. The interpolated velocity corresponding to t^* is the EDR-derived occupant impact velocity.

B.3.2 Occupant Ridedown Acceleration

As the NCAP acceleration data is sampled at least every millisecond, computation of the occupant ridedown acceleration is facilitated by a moving average as prescribed by NCHRP Report 350. Starting from the elapsed time to theoretical impact with the occupant compartment, a 10-ms moving average is performed on the filtered longitudinal acceleration information (CFC 180). The largest of these 10-ms averages becomes the longitudinal occupant ridedown acceleration.

For the GM EDR information, the NCHRP Report 350 procedure must be modified due to the inherent limitations of the data. Two problems exist: (1) the GM EDR provides only velocity information and (2) only provides this information in 10-ms increments. To obtain vehicle acceleration information, a derivative must be performed on the obtained numerical velocity information. Fitting a polynomial of n th degree may provide additional accuracy, however, a simple numerical slope computation has been performed on the EDR velocity information subsequent to the theoretical time of occupant impact. As the GM EDR provides this information in 10-ms increments, the computed derivative values are assumed to correspond to the 10-ms moving average acceleration values. The largest of these values is chosen as the EDR-based occupant ridedown acceleration.

B.4 Results

The results of the examination of these six NCAP tests are summarized in the tables and plots below. Table 11 presents a comparison between the NCAP and EDR-computed occupant impact velocity values. Similarly, Table 12 presents the numerical results for the NCAP and EDR-computed occupant ridedown acceleration values. Figure 70 and Figure 71 graphically illustrate the comparison between the occupant impact velocity and occupant ridedown acceleration computations, respectively. Refer to Figure 72 through Figure 83 at the end of this appendix for a graphical comparison of GM EDR and NCAP velocity and acceleration information in each NCAP test.

Table 11. Comparison of NCAP and EDR Occupant Impact Velocity Computations

NCAP Test Designation	NCAP Occupant Impact Velocity (m/s)	EDR Occupant Impact Velocity (m/s)	Error (%)
4487	16.86	16.34	3.1
4472	15.12	14.40	4.8
4244	15.79	15.17	3.9
4198	17.16	16.25	5.3
3952	17.12	16.95	1.0
3851	15.27	15.60	2.2

As indicated in Table 11 and Figure 70, there is a good agreement between the occupant impact velocities computed from the different data sources. Assuming the NCAP information to be the accurate value, the GM EDR estimated the actual occupant impact velocity within five (5) percent in most cases. Even in NCAP test 4198, where the GM EDR information had a time shift of approximately twenty (20) milliseconds with respect to the NCAP data, the error in the computation of the occupant impact velocity is only a mere five (5) percent. The agreement between the data suggests that the computation of the occupant impact velocity in single event frontal collisions can be accomplished through the use of the relatively coarse GM EDR information.

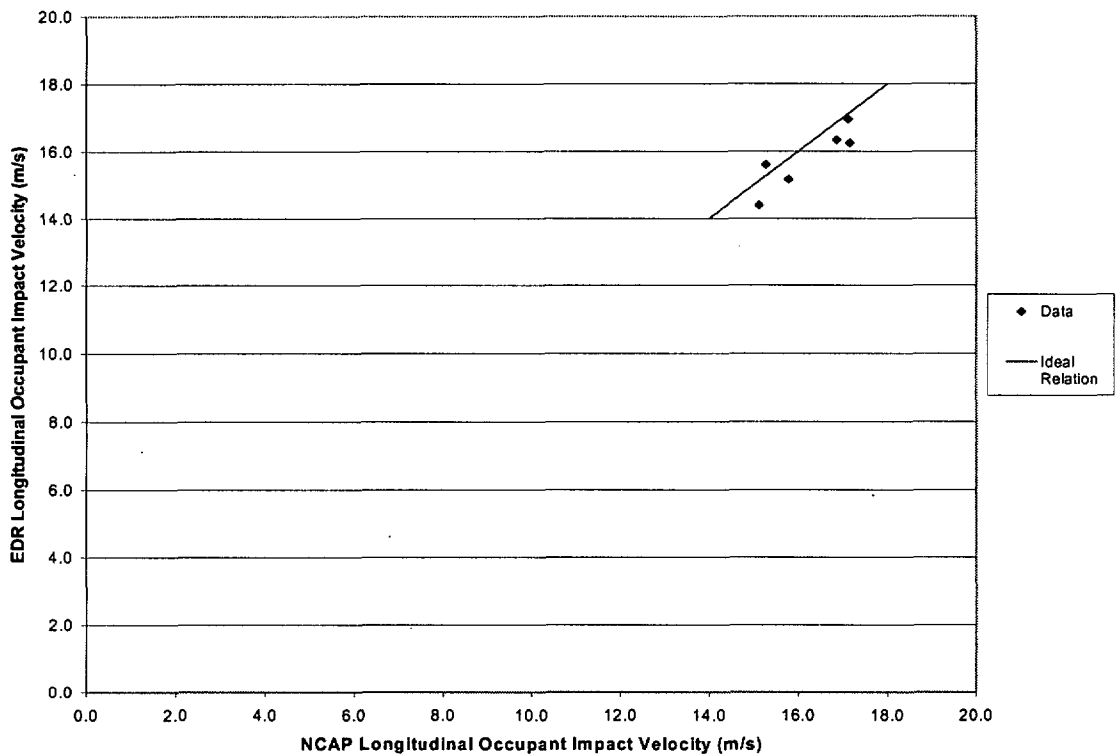


Figure 70. EDR and NCAP Occupant Impact Velocity Comparison

Due to the limitations of the GM EDR data, the level of agreement between the occupant ridedown acceleration values is not expected to be comparable to that of the occupant impact velocity. As expected, Table 12 indicates that the occupant ridedown acceleration as computed using the GM EDR data varies up to approximately seventy (70) percent of the NCAP value. Note, however, that the occupant ridedown is consistently over estimated when computed using the GM EDR velocity information. The average over estimation provided by the EDR data is approximately forty (40) percent. Although there is significant deviation in the computed values, the computation of the occupant ridedown acceleration using this methodology appears to provide an overly conservative estimate of the actual value, at least in the single event, frontal collision crash mode.

Table 12. Comparison of NCAP and EDR Occupant Ridedown Acceleration Computations

NCAP Test Designation	NCAP Occupant Ridedown Acceleration (G)	EDR Occupant Ridedown Acceleration (G)	Error (%)
4487	13.77	13.99	1.6
4472	11.98	16.96	41.6
4244	6.89	9.89	43.5
4198	6.51	10.99	68.7
3952	8.88	15.00	68.9
3851	10.88	11.99	10.2

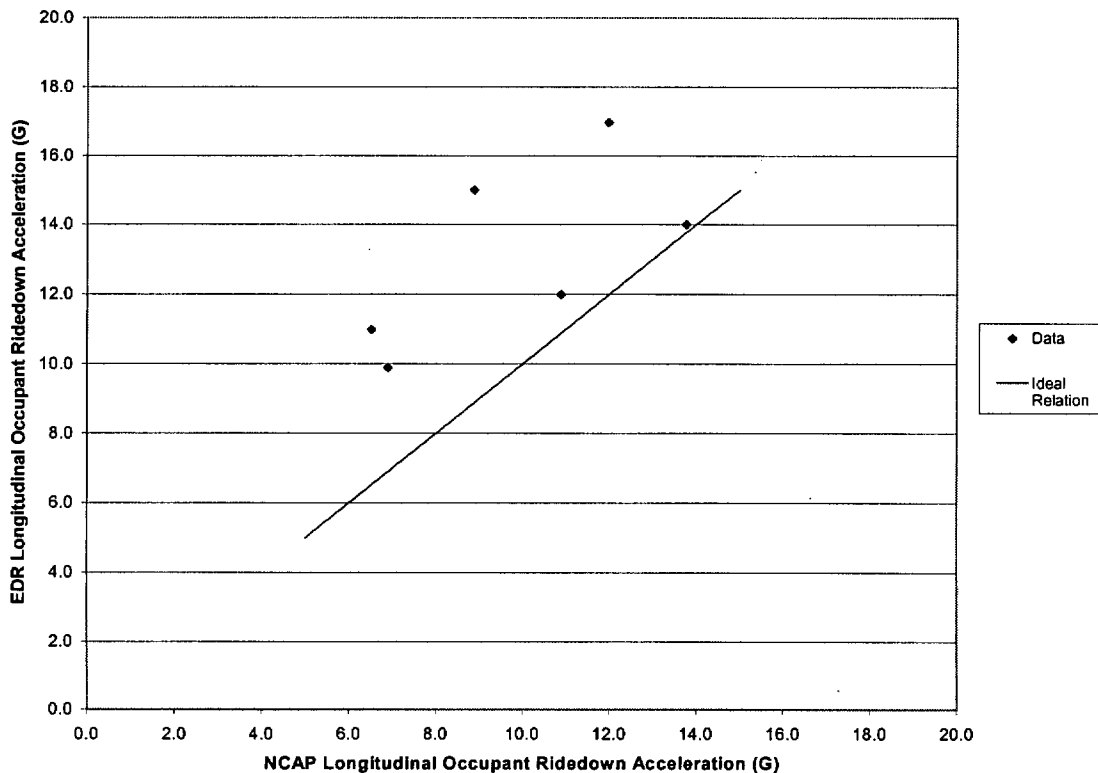


Figure 71. EDR and NCAP Occupant Ridedown Acceleration Comparison

B.5 Conclusions

The following conclusions have been drawn from the analysis of these six (6) NCAP tests:

1. In single event frontal collisions, GM EDR velocity data appears to be a viable source of data for the use of computing the occupant impact velocity. The maximum error in the analyzed data set is approximately five (5) percent.
2. For the computation of the occupant ridedown acceleration, the GM EDR velocity data provides a conservative estimate in single event frontal collisions. On average, the occupant ridedown acceleration values are over estimated by approximately forty (40) percent.

Although not as precise as the devices utilized in full-scale crash tests, the GM EDR can provide relatively accurate information regarding the vehicle kinematics during a single event frontal collision.

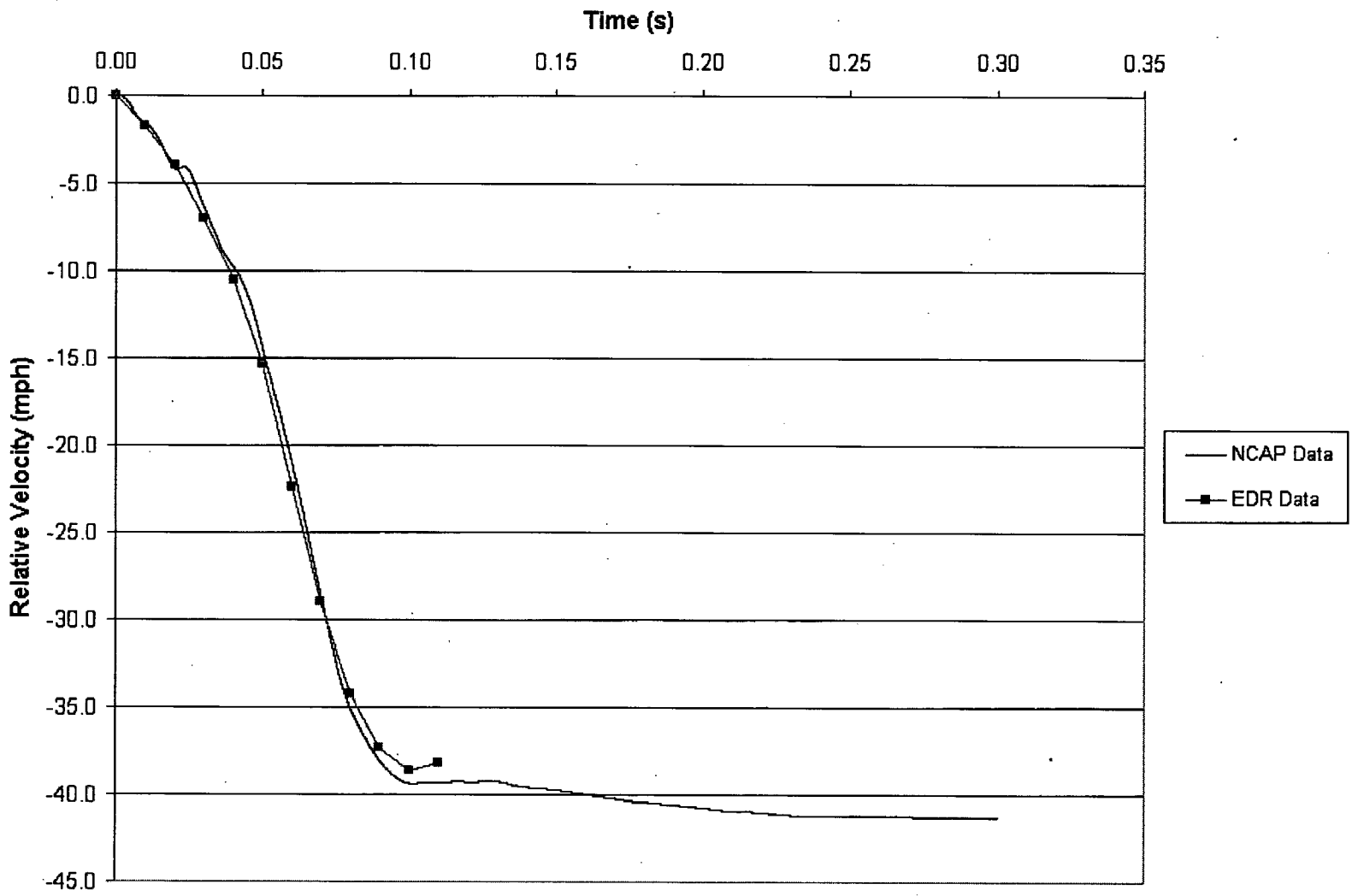


Figure 72. NCAP Test 4487: Velocity Comparison

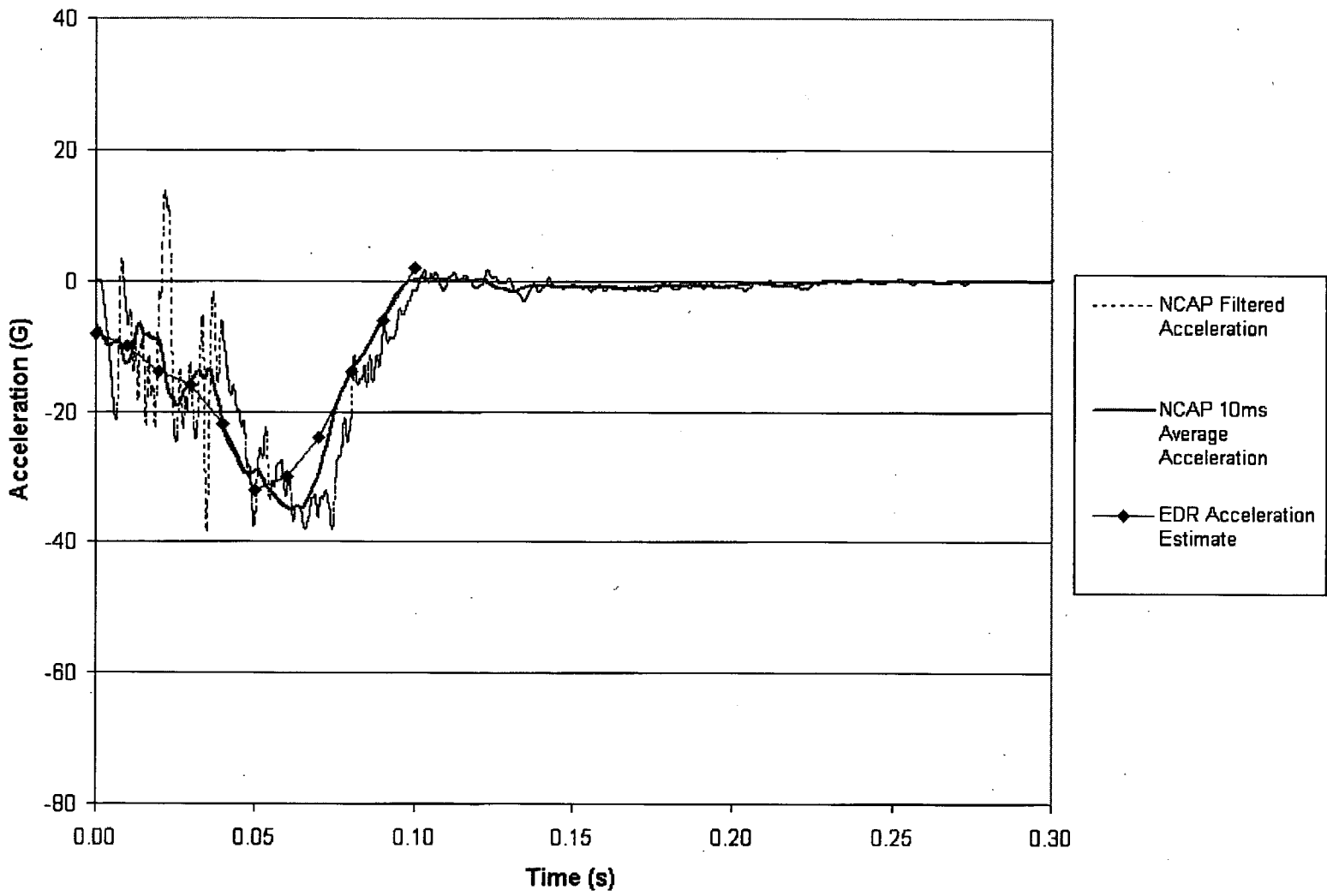


Figure 73. NCAP Test 4487: Acceleration Comparison

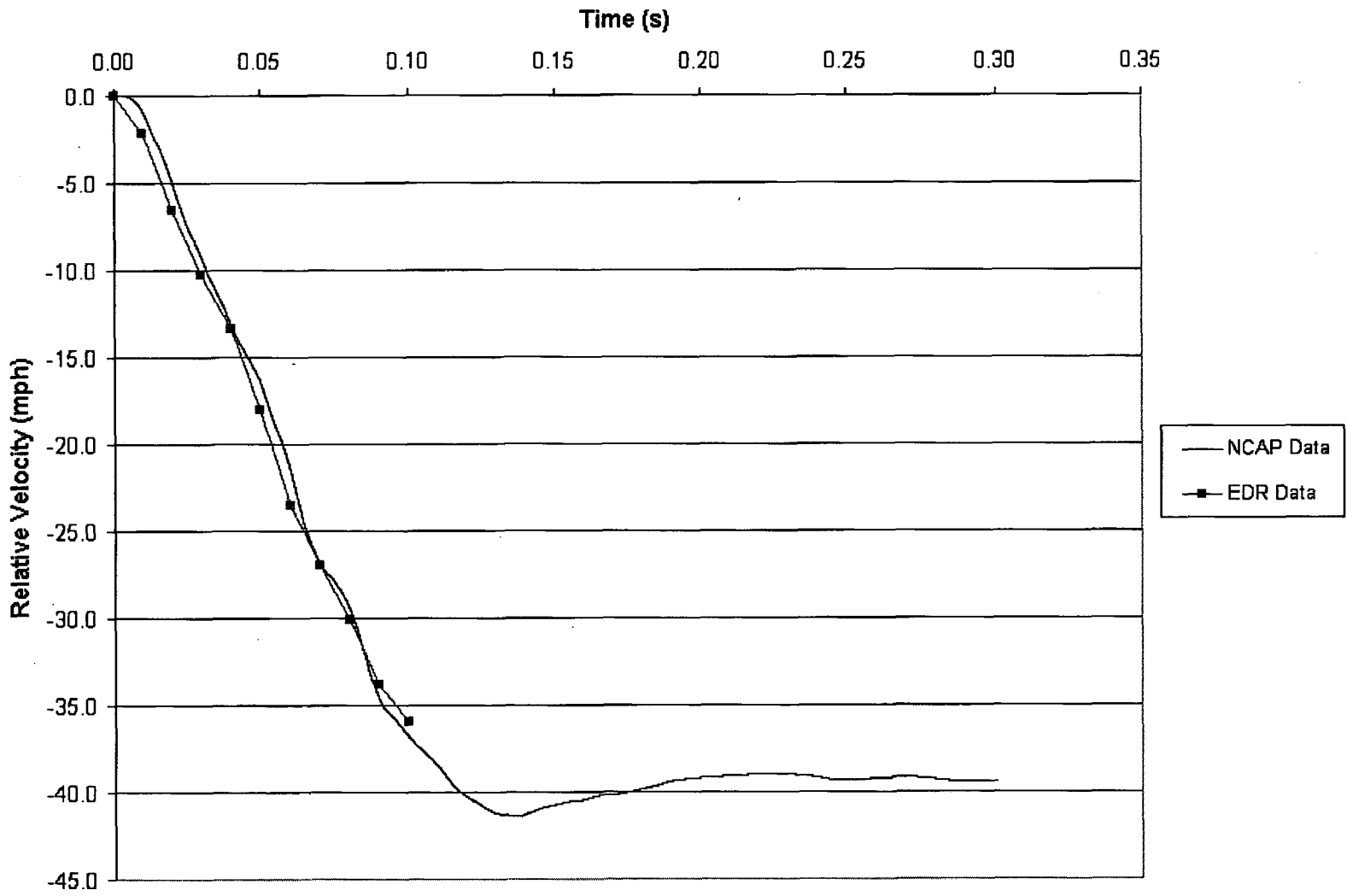


Figure 74. NCAP Test 4472: Velocity Comparison

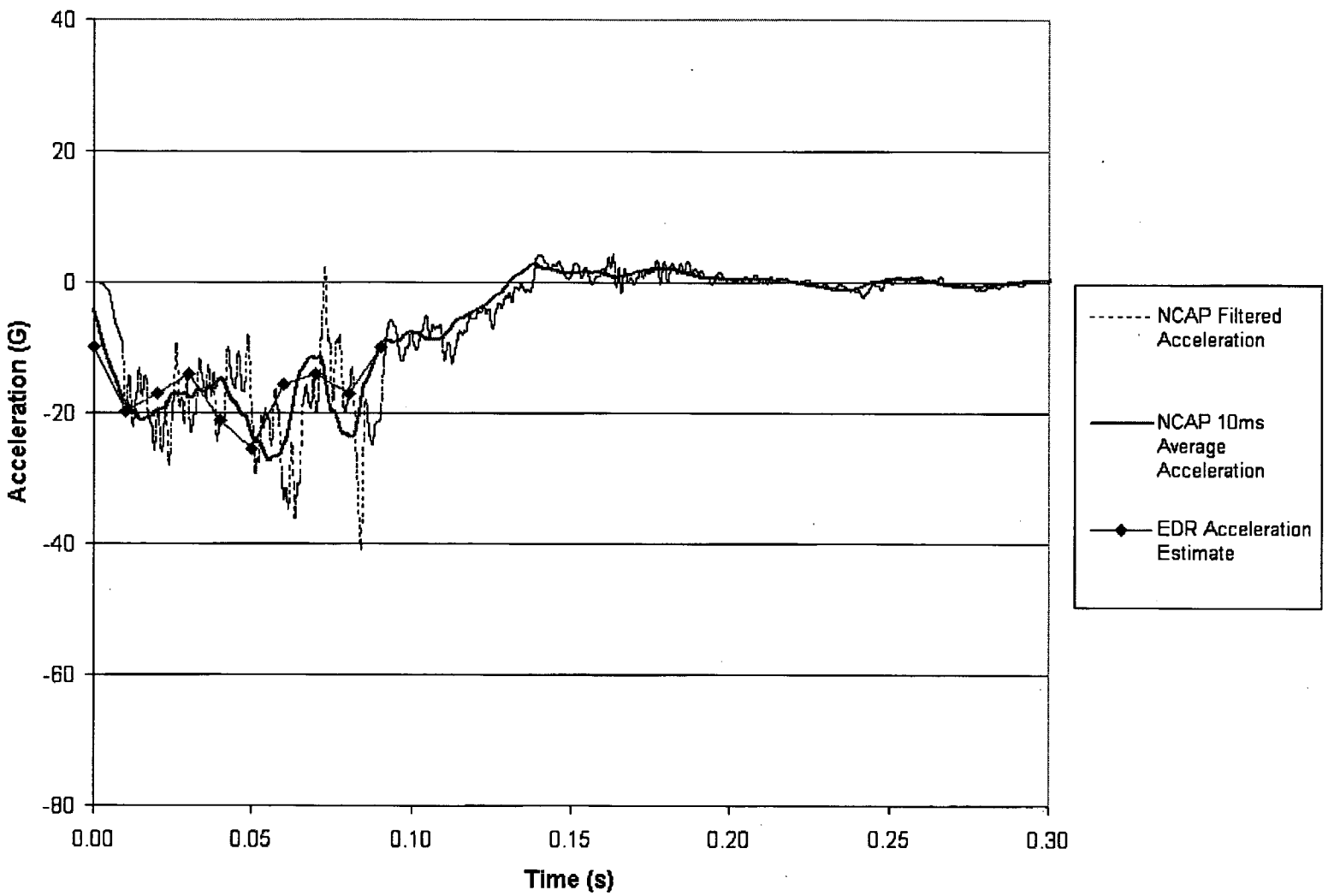


Figure 75. NCAP Test 4472: Acceleration Comparison

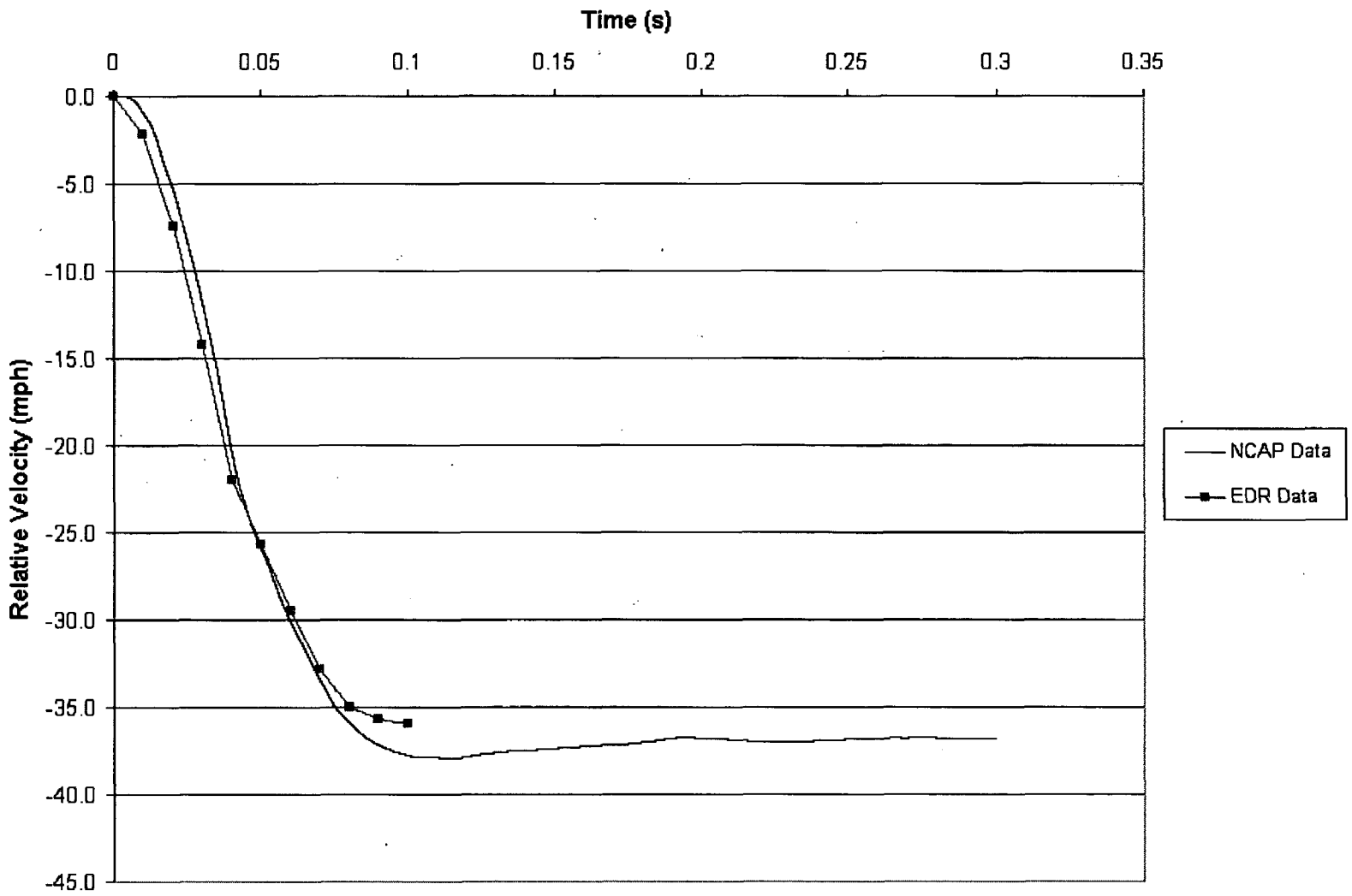


Figure 76. NCAP Test 4244: Velocity Comparison

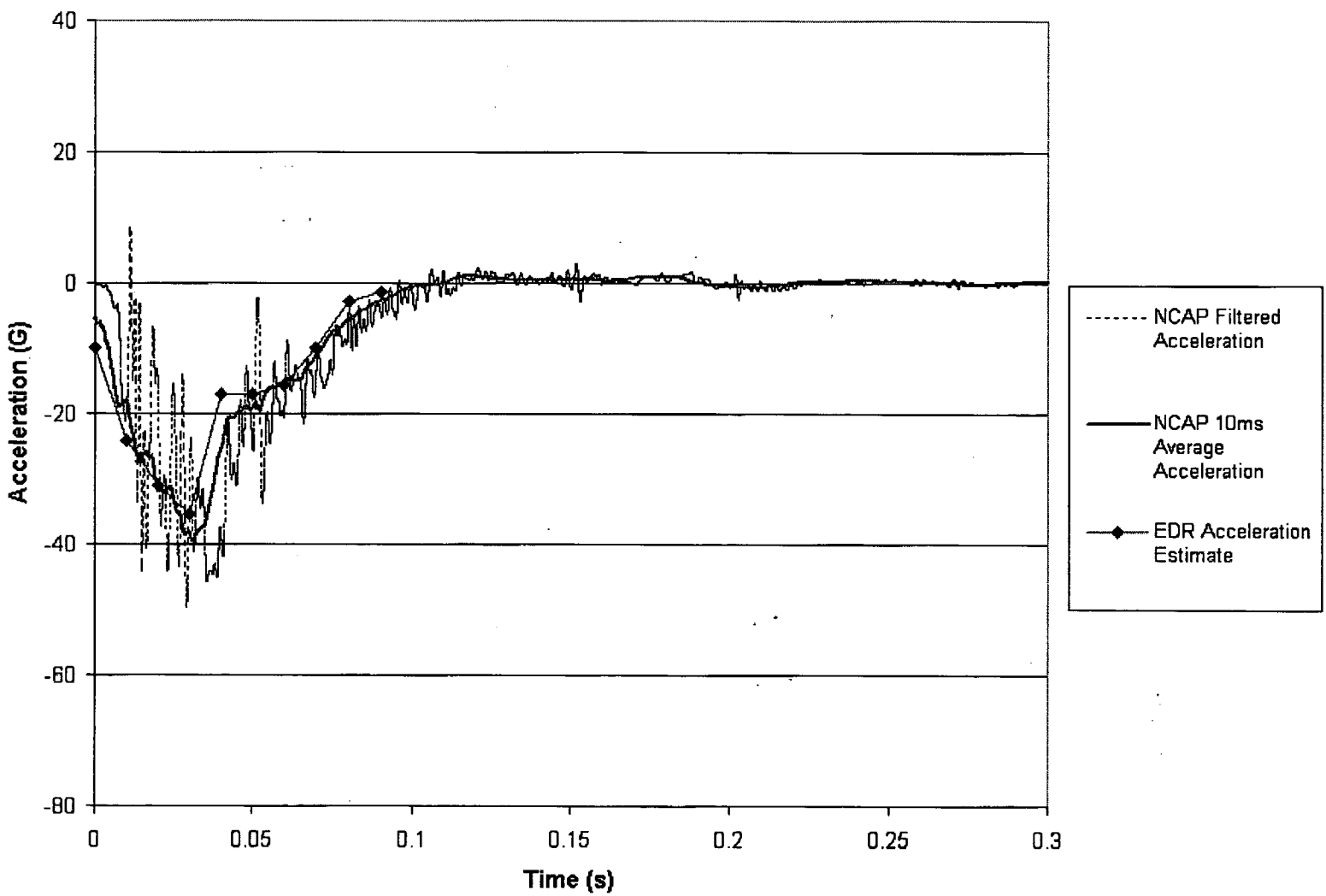


Figure 77. NCAP Test 4244: Acceleration Comparison

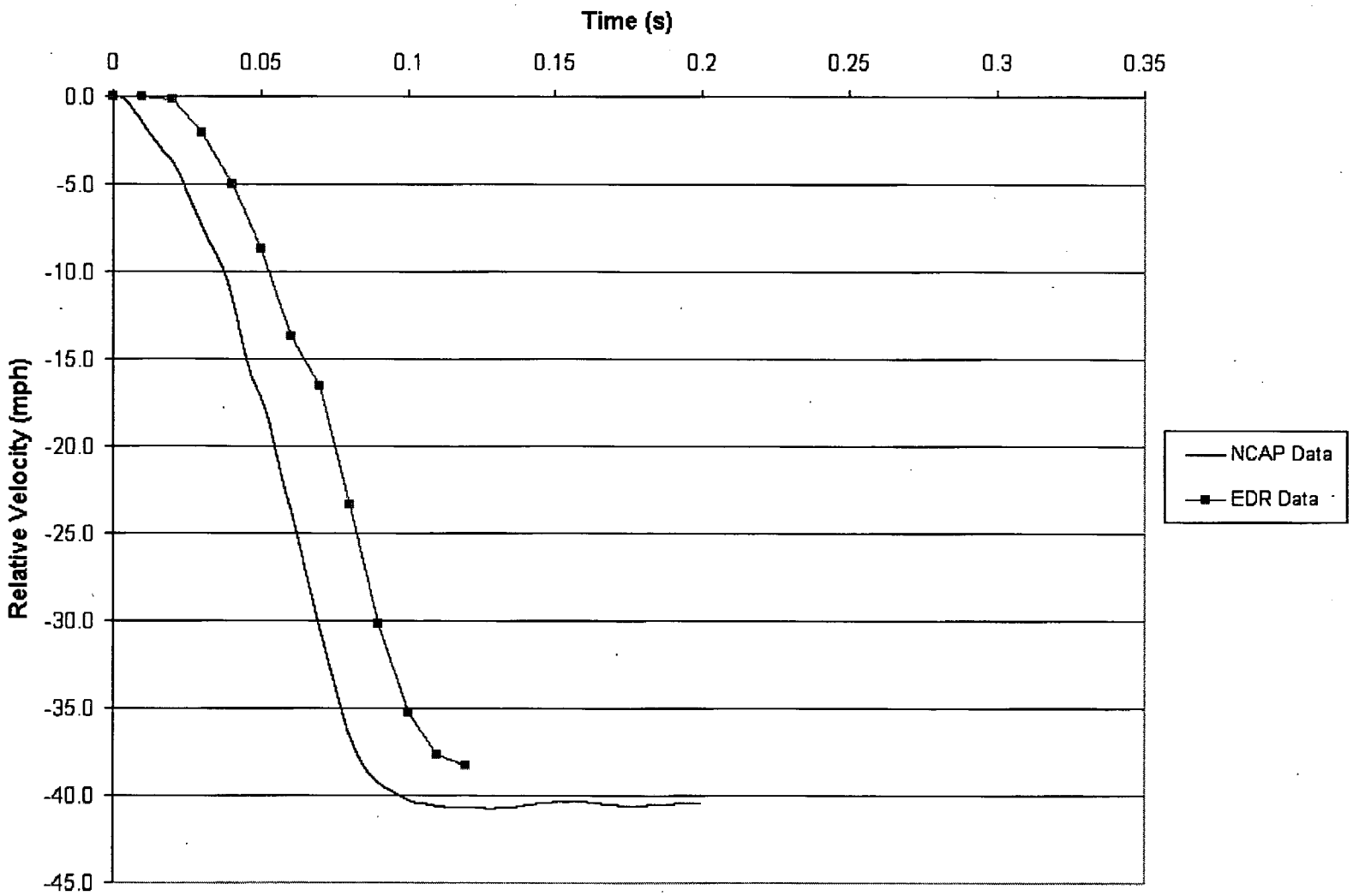


Figure 78. NCAP Test 4198: Velocity Comparison

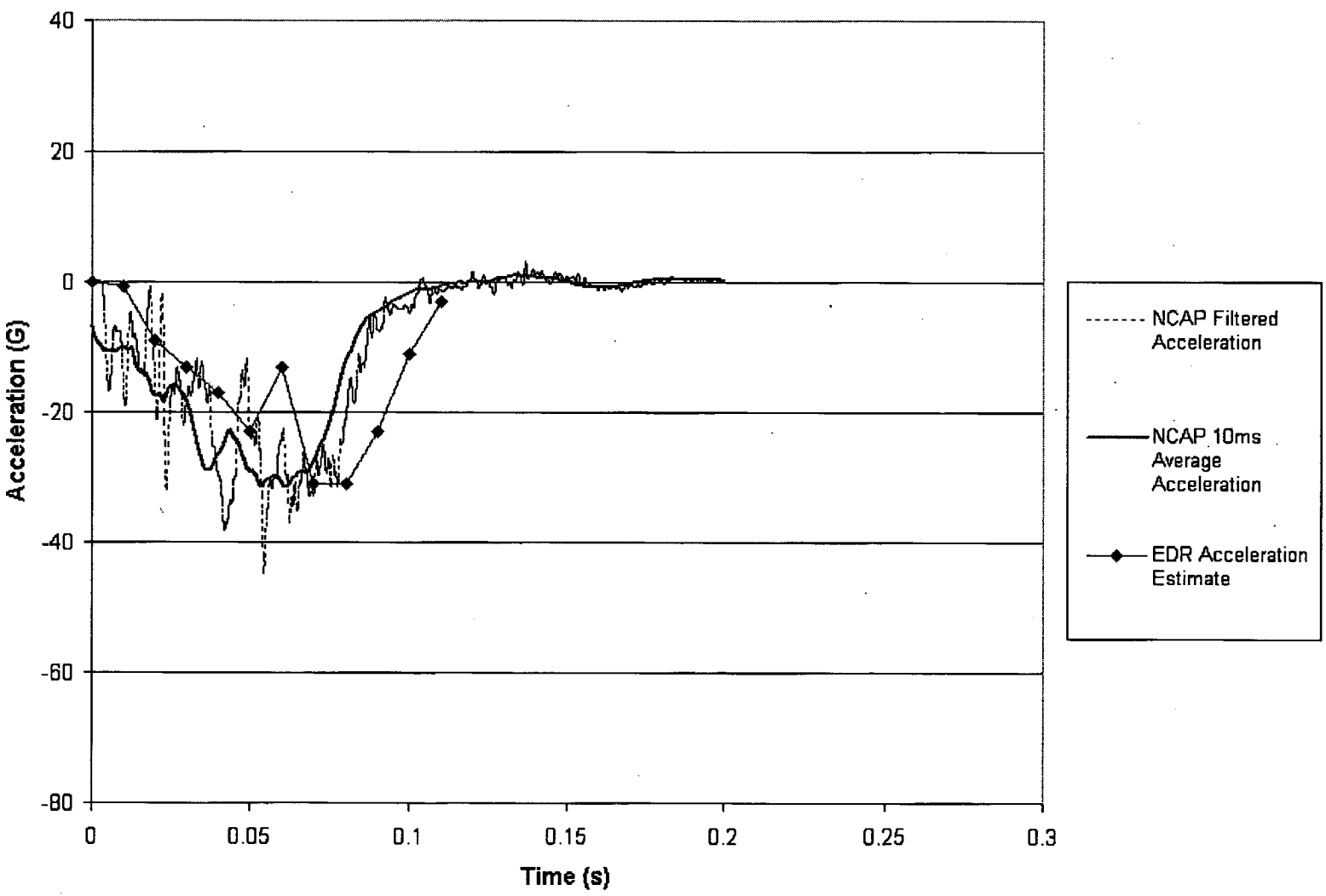


Figure 79. NCAP Test 4198: Acceleration Comparison

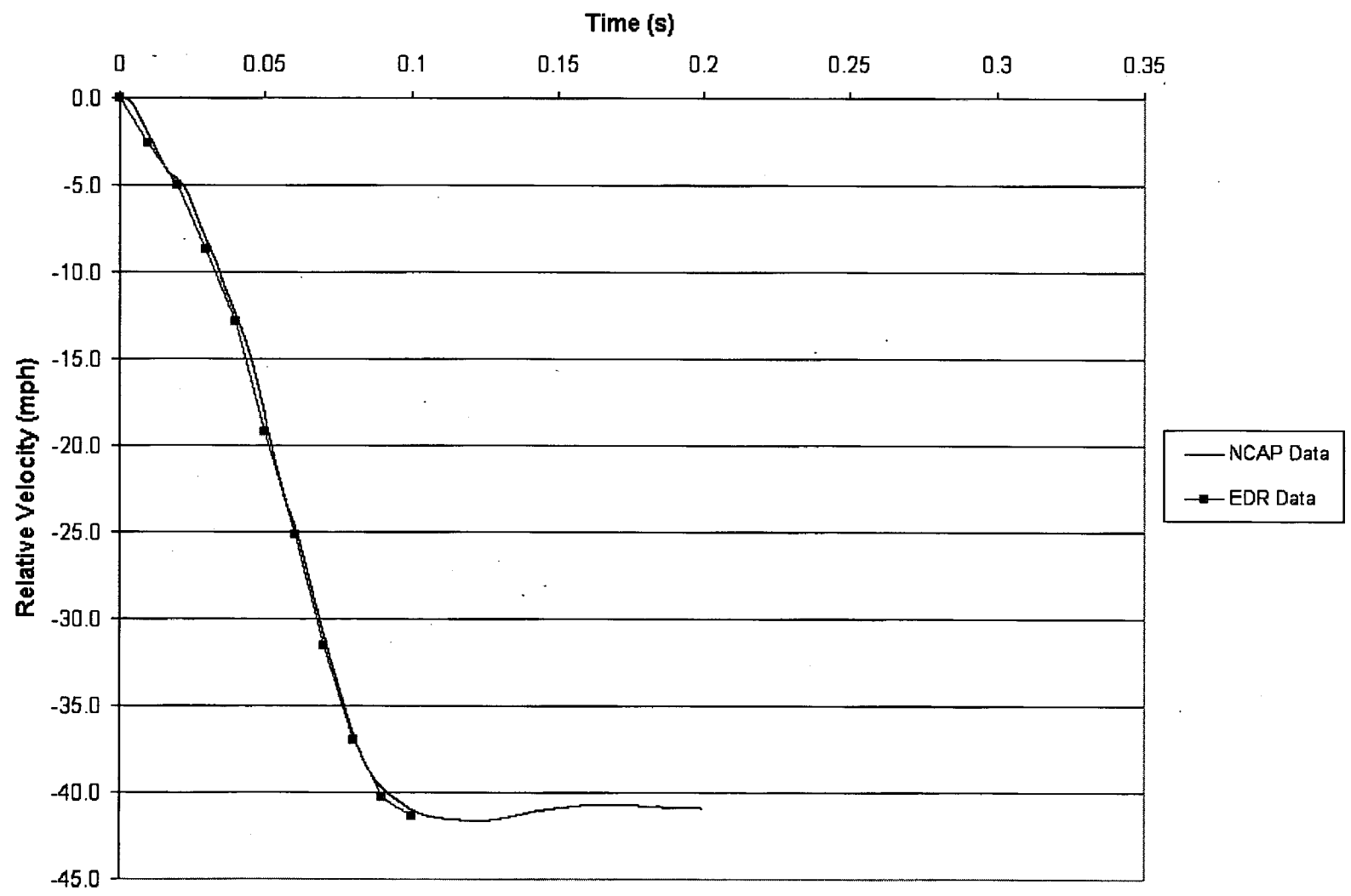


Figure 80. NCAP Test 3952: Velocity Comparison

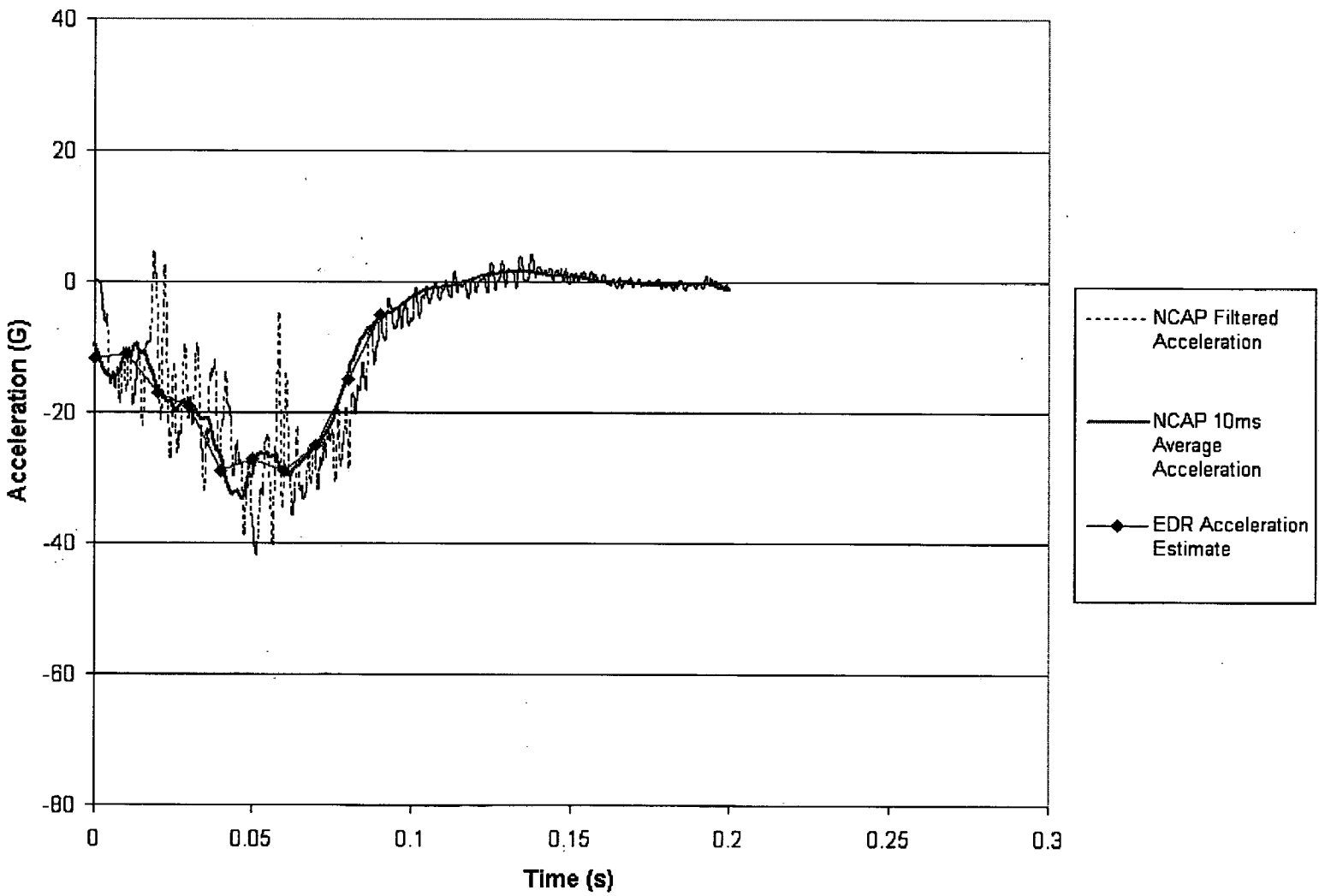


Figure 81. NCAP Test 3952: Acceleration Comparison

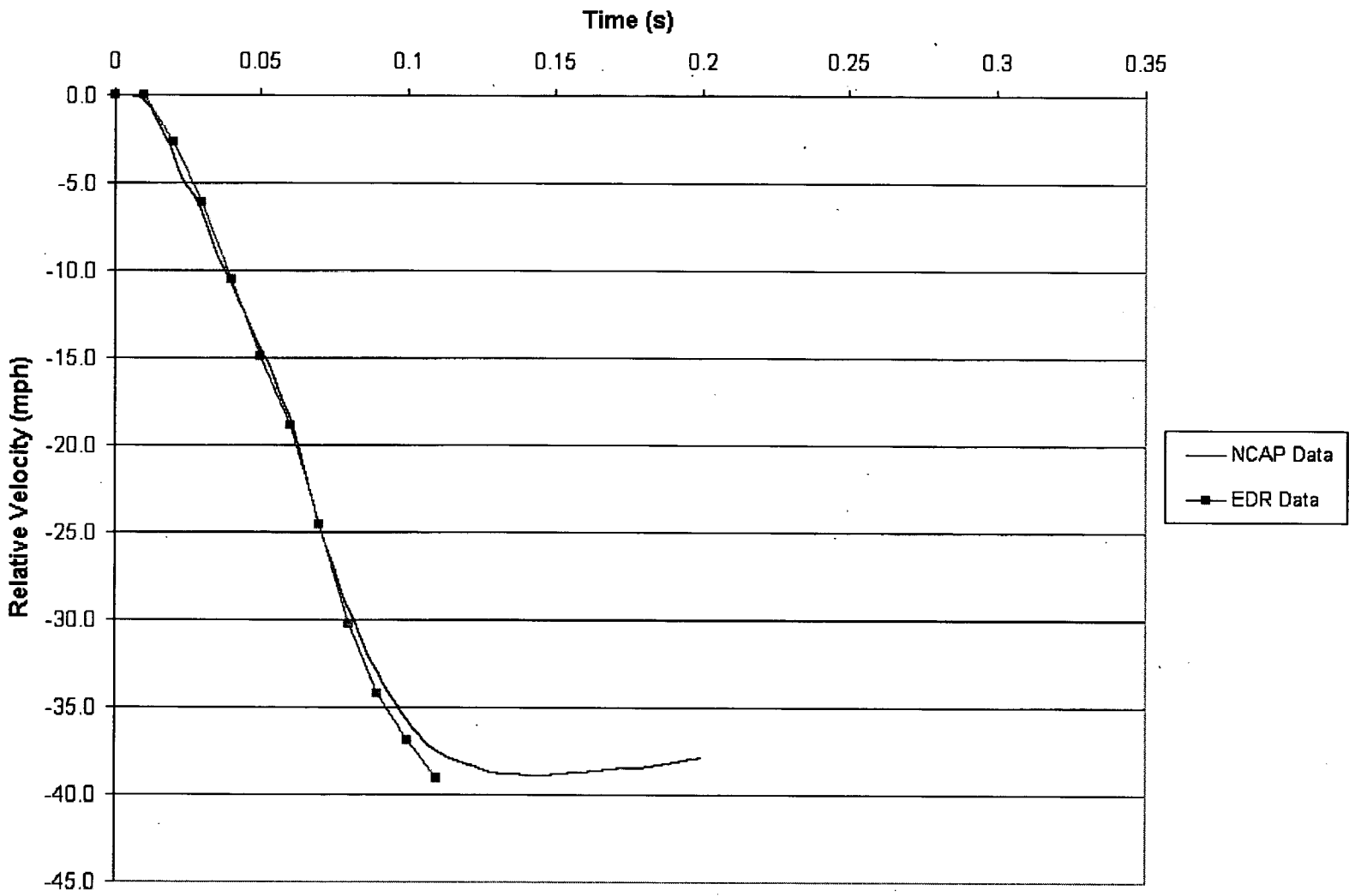


Figure 82. NCAP Test 3851: Velocity Comparison

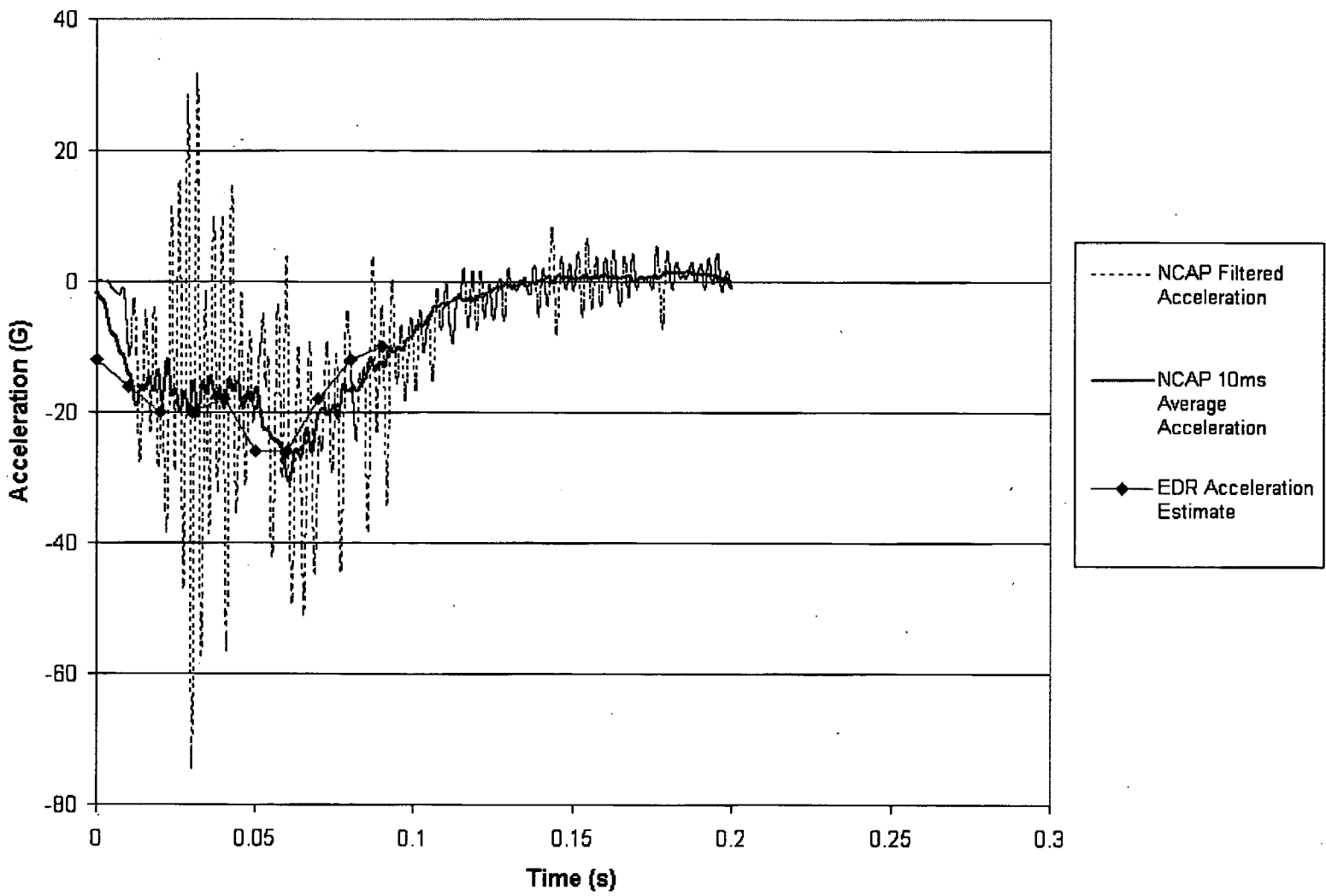


Figure 83. NCAP Test 3851: Acceleration Comparison